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DESIGN INTEGRATION AND NOISE STUDIES FOR JET STOL AIRCRAFT

Task VIIA

AUGMENTOR WING CRUISE BLOWING VALVELESS SYSTEM

Volume I—System Design and Test Integration

By F. A. Roepcke and T. B. Nickson

Prepared under Contract NAS2-6344 by
BOEING COMMERCIAL AIRPLANE COMPANY

P.O. Box 3707
Seattle, Washington 98124

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16. Abstract

Exploratory design studies conducted by The Boeing Company to establish the configuration of an augmentor wing cruise blowing (valveless) system in a 150-passenger STOL airplane were reported in NASA CR-114570. Those studies have been updated to incorporate the results of static rig, flow duct, and wind tunnel tests. Minor adjustments in duct flow velocity, flap length, and blowing nozzle geometry were incorporated to provide airplane characteristics that minimize takeoff gross weight and achieve sideline noise objectives for an advanced commercial STOL airplane.

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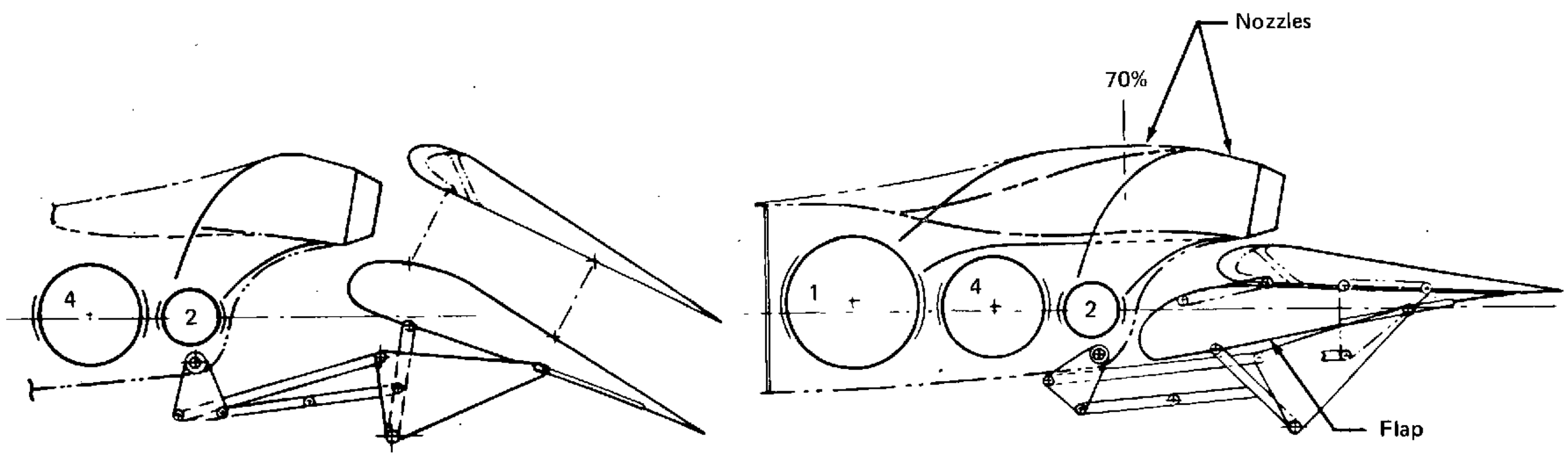
1.0 SUMMARY

Task VII of contract NAS2-6344 was implemented in March 1972 by The Boeing Company which, through exploratory design, static performance and noise tests, and small-scale wind tunnel tests, defined a selected cruise blowing valveless augmentor wing system to be further evaluated in the Ames 40- by 80-ft wind tunnel.

Figure 1 illustrates the cruise blowing system concept, which eliminates flow diverter valves and separate cruise nozzles. The fan air is directed to the wing ducts, with a portion used for leading edge and aileron boundary layer control. The major part of the air discharges from multielement lobed nozzles through acoustically lined flaps in the augmentor mode. In the cruise mode the flaps are retracted, and the air continues to blow over the flap upper surface.

The initial exploratory design studies resulting in blowing system configuration and sizing data for a projected commercial STOL transport airplane are reported in reference 1 (CR-114570). The studies included a range of augmentor and wing geometry variables based on a four-engine, 150-passenger airplane with 2000-ft FAR field length and 90-PNdB noise level objective at 500-ft sideline. The cruise requirement was 30 000-ft altitude at Mach 0.8 with a STOL range of 500 nmi and alternate mission CTOL range of 1500 nmi.



Takeoff Position **Cruise Position**

FIGURE 1.—AUGMENTOR WING CRUISE BLOWING FLAP CONCEPT

The following configuration data were selected for test hardware implementation:

Engine fan pressure ratio	3.2
Wing nozzle pressure ratio	2.7
Wing thickness, t/c	$0.132_{outboard}$, 0.176_{SOB}
Wing sweep angle (0.25c)	25°
Wing aspect ratio, AR	7.5
Flap chord	0.26c
$\Delta P/P_F$	0.082
Wing thrust loading, $(T/S)_{un}$	32.2 psf

The projected airplane characteristics were:

TOGW	191 500 lb
Wing loading, W/S	84.0 psf
$SLST_{(un)}$, four engines at	18 300 lb

With completion of the testing portions of the program (task V, augmentor static rig tests, ref. 2 (CR-114534); task VIIB, high-speed wind tunnel tests, ref. 3 (CR-114560); task VIIC, vol. I, augmentor static rig tests, ref. 4 (CR-114622); and task VIIC, vol. II, duct flow rig tests, ref. 5 (CR-114623)), applicable test results were used as a basis for adjusting the augmentor system and updating the airplane characteristics.

The air distribution duct performance was adjusted with an increased loss assigned to the engine fan collector and air offtake duct, a decrease in wing duct wye loss, and an increased loss in the wing duct runs in the vicinity of the nozzle air offtakes. The combined effect of these changes reduced the estimated airflow capacity (and the wing thrust loading, $(T/S)_{un}$) of the system at any given overall pressure drop, $\Delta P/P_F$, compared with that of the system defined in reference 1. The wing of the reference 1 airplane was sized for $\Delta P/P_F = 0.082$ yielding $(T/S)_{un} = 32.2$ psf in the 2280-sq-ft, AR = 7.5 planform with $t/c = 0.132_{outboard}$, $0.176_{side\ of\ body}$. If the wing size in reference 1 had been reduced so that flow velocities increased to give $\Delta P/P_F = 0.10$, the wing thrust loading would have been 36 psf. This compares with 34.8 psf in the current updated system operating at $\Delta P/P_F = 0.10$.

Test data showed that thrust augmentation and flow-turning performance in the flap with the cruise blowing nozzle configuration were lower than previously assumed. To satisfy the airplane noise goal of 90-PNdB peak noise on a 500-ft sideline, it was necessary to reduce the array area ratio of the augmentor nozzles from 8.0 to 6.0, which further degraded thrust augmentation. Compared with 1.30 assumed in the exploratory studies, the resulting static augmentation ratio, ϕ, is 1.20 for the takeoff flap setting. The derivation of this augmentor performance is consistent with the methods used in reference 2 (CR-114534).

It should be noted that the demonstrated augmentation ratios of reference 4 static rig tests were achieved with a minimal test program using a single set of hardware. Some improved performance should be obtained from further optimization.

The trade of augmentation, noise, duct loss, and wing aspect ratio with wing thrust loading is given in figure 2.

In refining the airplane configuration, estimates of the parasitic drag and jet efflux scrubbing drag of the cruise blowing nozzles were roughly doubled to reflect the results of the high-speed wind tunnel test. Airplanes were evaluated with 7.5 and 8.0 aspect ratio wings and with assumed duct flow velocities corresponding to duct losses, $\Delta P/P_F$, of 0.10 and 0.12. Although the higher aspect ratio wings met the 90-PNdB noise goal, they were cruise thrust limited with resulting excessive takeoff weights.

A comparison of the final series of configurations is given in figure 3 in terms of augmentor noise versus takeoff gross weight. The optimum wing aspect ratio for a minimum weight airplane meeting the noise goal is approximately 7.5 with the augmentor duct system operating at $\Delta P/P_F$ = 0.10. A moderate increase in $\Delta P/P_F$ (to 0.11, for example) would yield higher wing thrust loading, $(T/S)_{un}$, and permit lower gross weight, but would exceed the noise goal. Sizing parameters with cruise thrust, takeoff thrust, fuel volume, and duct volume constraints are plotted in figure 4 for the selected configuration. The general arrangement of the airplane is presented in figure 5.

Characteristics of the airplane and system are as follows:

TOGW	195 800 lb
Wing loading, W/S	84.8 psf
Wing aspect ratio, AR	7.5
Wing sweep angle (0.25c)	25°
Wing thickness, t/c	$0.132_{outboard}$, 0.176_{SOB}
$SLST_{(un)}$, four engines at	20 120 lb
Peak noise at 500-ft sideline	90 PNdB

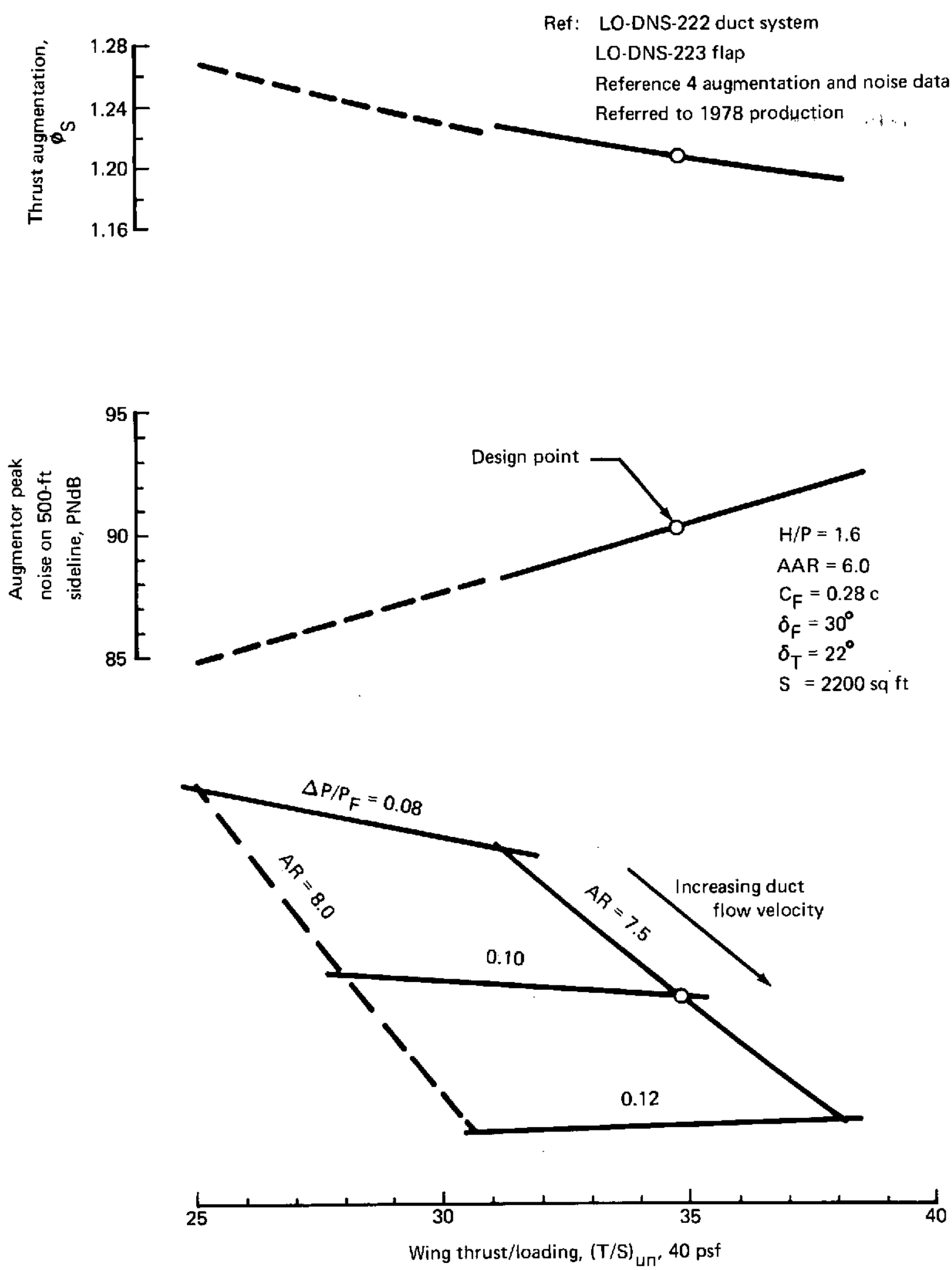
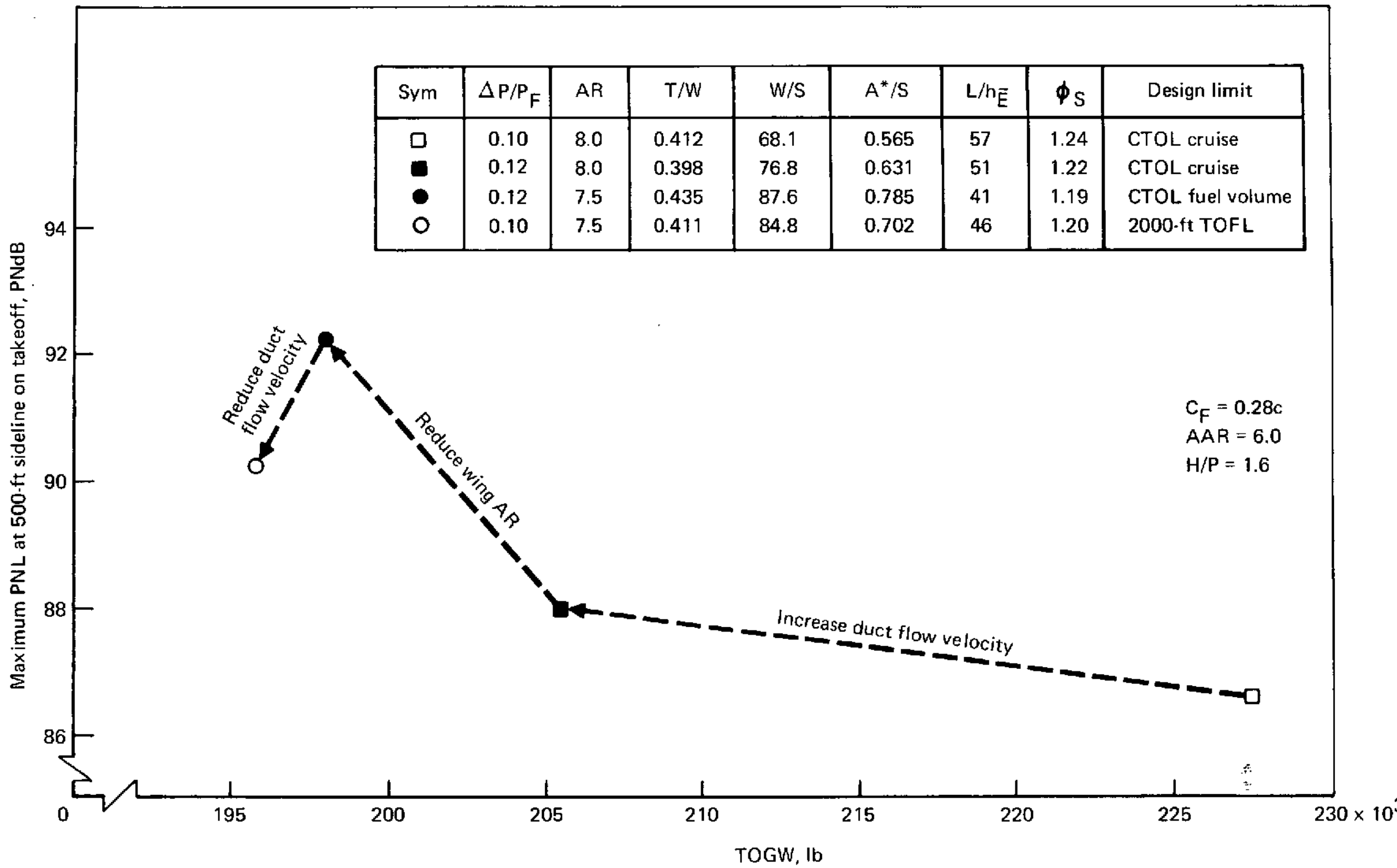


FIGURE 2.—THRUST AUGMENTATION AND NOISE AS FUNCTIONS OF WING THRUST LOADING, ASPECT RATIO, AND DUCT FLOW LOSS



Sym	$\Delta P/P_F$	AR	T/W	W/S	A*/S	$L/h_{\bar{E}}$	ϕ_S	Design limit
□	0.10	8.0	0.412	68.1	0.565	57	1.24	CTOL cruise
■	0.12	8.0	0.398	76.8	0.631	51	1.22	CTOL cruise
●	0.12	7.5	0.435	87.6	0.785	41	1.19	CTOL fuel volume
○	0.10	7.5	0.411	84.8	0.702	46	1.20	2000-ft TOFL

FIGURE 3.—NOISE AND WEIGHT TRADEOFFS, TASK VII DESIGN

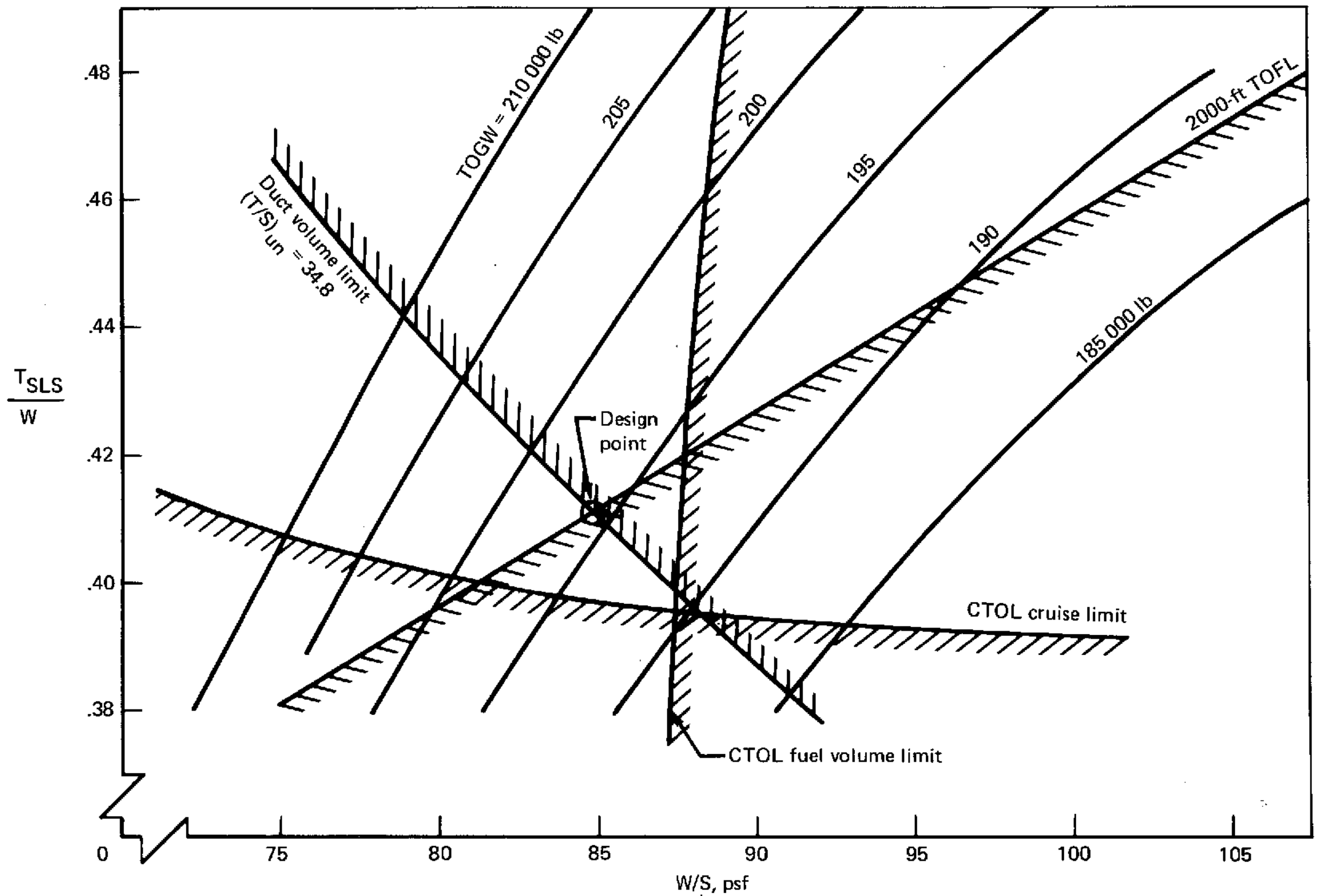


FIGURE 4.—AUGMENTOR WING CRUISE BLOWING SYSTEM AIRPLANE SIZING PARAMETERS (AR = 7.5, $\Delta P/P_F = 0.10$)

- Payload . . . . 150 passengers
- Range (STOL) . . . . 500 nmi
- Range (CTOL) . . . . 1500 nmi
- TOGW (STOL) . . . . 195 800 lb
- TOGW (CTOL) . . . . 241 900 lb
- OEW . . . . 136 800 lb
- Engines . . . . Four P&WA STF-395D (BM-2) At 20 100 lb SLS
- Fuel capacity . . . . 81 000 lb
- W/S (STOL) . . . . 84.8 psi
- T/W (STOL) 0.41
- Wing
  - Area . . . . 2309 sq ft
  - Aspect ratio 7.5
  - Sweep (0.25c) . . . . . . 25°
  - t/c 0.176, 0.132
- Tail volume
  - Horizontal 1.10
  - Vertical 0.107
- Noise (takeoff) . . . . 90 PNdB peak at 500-ft sideline

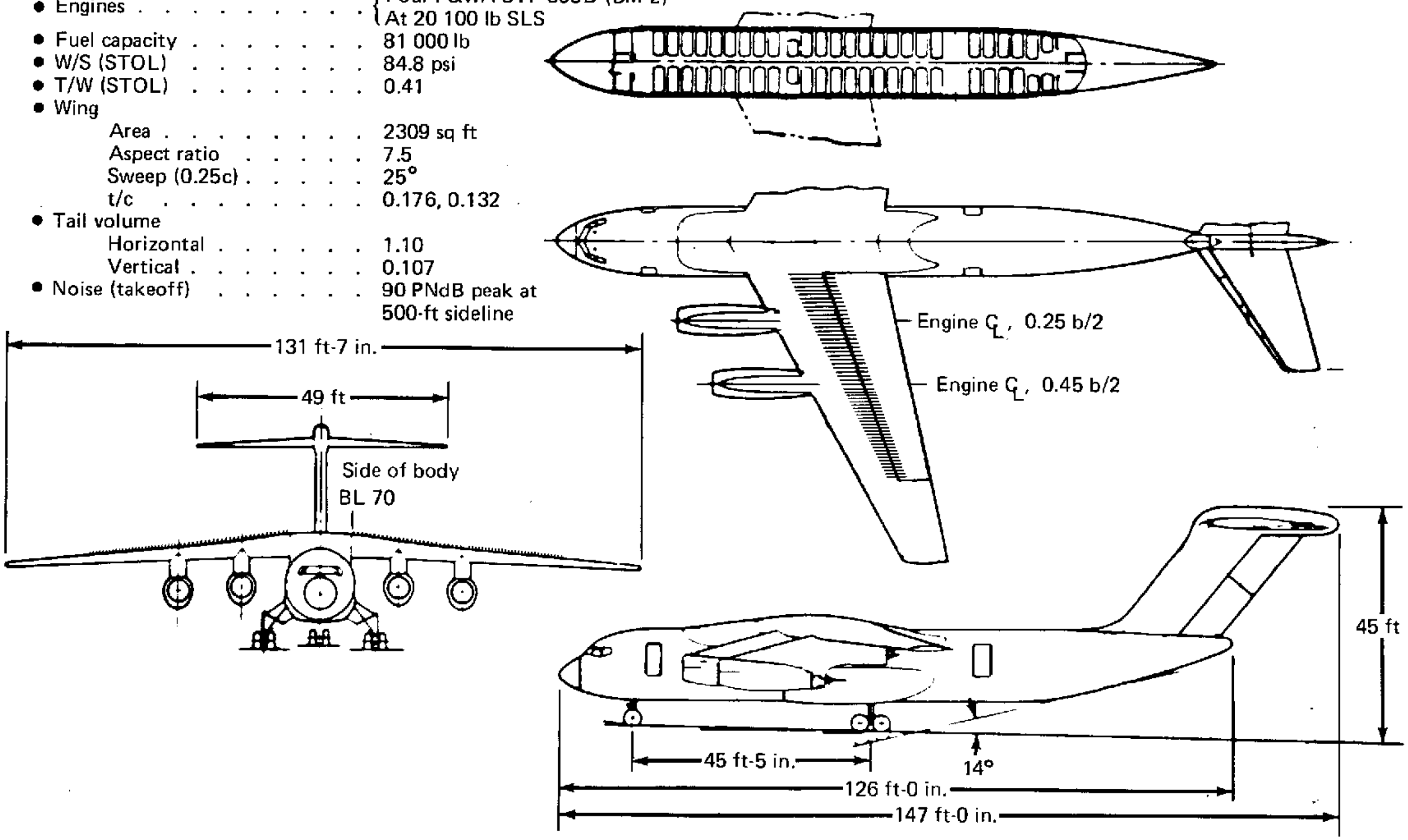


FIGURE 5.—GENERAL ARRANGEMENT, AUGMENTOR WING AIRPLANE WITH CRUISE BLOWING VALVELESS SYSTEM

2.0 INTRODUCTION

Studies of the augmentor wing powered-lift concept have shown that the inherent ejector-suppressor characteristics of the system can result in a commercial STOL airplane with lower noise potential than other systems proposed. The characteristics were verified through design and test work completed by The Boeing Company in March 1972, under tasks I, II, and III of contract NAS2-6344, "Design Integration and Noise Studies for a Large STOL Augmentor Wing Transport." Pertinent results of that program are reported in reference 6.

Task VII of contract NAS2-6344 is divided into subtasks to define an airplane system that takes advantage of the noise suppression and powered-lift performance of the augmentor wing in the takeoff and landing approach modes and that utilizes the augmentor nozzles for thrust in the cruise mode. During cruise the augmentor flaps are stowed, and the wing nozzles blow over the upper surface. The complexity and weight of diverter valves and separate nozzles for cruise operation are thus eliminated.

Exploratory system studies were undertaken in task VIIA (ref. 1) to establish hardware design parameters for the testing portions of the program. These studies encompassed an engine fan pressure ratio down to 1.5 in an effort to achieve a commonality with other potential STOL propulsion systems. Task VIIB high-speed, two-dimensional wind tunnel tests of the cruise blown wing are reported in reference 3; task VIIC augmentor static rig and duct flow rig tests are reported in references 4 and 5.

This document reports the adjustment of the augmentor system and the updating of the airplane characteristics to incorporate the results of these tests.

3.0 SYMBOLS AND ABBREVIATIONS

A^*	blowing nozzle area at Mach 1.0, sq in.
A_A/S	augmentor nozzle area, sq in./sq ft of wing area
A_N/S	total wing nozzle area, sq in./sq ft of wing area
AAR	augmentor primary nozzle array area ratio, area enclosed by array/nozzle flow area
AR	wing aspect ratio, b/h, or nozzle aspect ratio, $b_{aug}/h_{\bar{E}}$
ail	aileron
BLC	boundary layer control
b	span, ft or in.
C_D	drag coefficient or nozzle discharge coefficient (measured mean airflow/ideal airflow)
C_d	sectional drag coefficient
C_F, C_f	flap chord, percent wing chord
C_J	total blowing momentum coefficient, augmentor primary nozzle isentropic thrust/qS
C_j	sectional blowing momentum coefficient, augmentor primary nozzle isentropic thrust/q x sectional area
C_V	nozzle velocity coefficient, measured thrust/(measured mass flow x ideal velocity)
CTOL	conventional takeoff and landing
c	local wing chord, in.

D	drag, lb
d	diameter, in.
F	augmentor primary nozzle thrust, lb
FPR	fan pressure ratio
H/P	nozzle height/spacing pitch
h	height, Y direction, in.
hp	horsepower
L	length, usually X direction, in.
LE	leading edge
M	Mach number
NA	not applicable
NPR	nozzle pressure ratio
OEW	operating empty weight, lb
P	total pressure, psi
PNdB	unit of perceived noise level
PNL	perceived noise level, PNdB
S, S_W	wing area, sq ft
SFC	specific fuel consumption, lb/hr/lb thrust
SLS	sea level static
SOB	side of body

STOL	short takeoff and landing
T	airplane net thrust, lb; temperature, °F
TE	trailing edge
TIT	high-pressure turbine inlet temperature at stator inlet, °R
T/O	takeoff power setting
TOFL	takeoff field length, ft
TOGW	takeoff gross weight, lb
T/S	wing thrust loading, airplane thrust/wing area ratio, psf
T/W	airplane thrust/weight ratio, lb/lb
t/c	wing thickness ratio, thickness/chord
V	velocity, ft/sec
W/S	wing loading, psf
$\Delta P/P_F$	fan air total pressure loss fraction relative to fan exit total pressure
$(\Delta P_T/q)_{diff}$	diffuser total pressure losses referenced to dynamic pressure of the mixed flow in the diffuser
$(\Delta P_T/q)_{inlet}$	inlet total pressure losses referenced to inlet dynamic pressure
δ_F	flap rotation angle with respect to wing chord plane, deg
δ_N	augmentor primary nozzle deflection angle with respect to wing chord plane, deg
δ_T	turning angle, deg ($\delta_T = \delta_F - \delta_N$)
Λ	airplane wing sweep of quarter chord, deg
ϕ	thrust augmentation; flaps on thrust/flaps off thrust

Subscripts:

A	aircraft
aug	augmentor
cr	cruise
E	equivalent slot nozzle area, sq in.
ENG	bare engine
F	fan exit total conditions
N	net or nozzle
MCR	maximum cruise rating
S	static
SLS	sea level static
SOB	side of body
STR	streamwise
un	uninstalled

4.0 SYSTEM AND TEST DATA INTEGRATION

The design studies of reference 1 covered a wide range of augmentor system variables, including pressure ratio, wing thickness, and aspect ratio. Ground rules for the study vehicle were as follows:

- 150-passenger airplane
- 2000-ft takeoff field length (FAR)
- 500-nmi STOL range
- 1500-nmi CTOL range
- Mach 0.8 at 30 000-ft cruise altitude
- 90-PNdB maximum takeoff noise objective at 500-ft sideline
- 1978-80 initial production goal

Engine fan pressure ratio as an independent variable had a substantial influence on both the configuration and performance of systems that would satisfy airplane requirements. The volume of air to be handled in a system with a low-pressure (P/P = 1.5), single-stage fan was not compatible with the concept of directing all the fan air through the wing. The resulting portion of fan exhaust issuing from the nacelle produced estimated peak sideline noise of 103 PNdB compared with the 90-PNdB objective. The airplane, with four engines at 34 700-lb SLST (uninstalled), had an estimated takeoff gross weight of 232 000 lb.

A higher fan pressure ratio of 3.5 reduced the estimated airplane gross weight to 186 700 lb. This pressure ratio was not regarded as an acceptable base for sizing test hardware because of the additional development requirement for a four-stage engine fan and because of the possible technical risks (flutter and drag rise) inherent in assuming an 8.5 wing aspect ratio and $t/c = 0.157_{\text{outboard}}, 0.201_{\text{side of body}}$.

More conservative assumptions were therefore incorporated, resulting in the following configuration characteristics. These data were used as a basis for the small-scale model in the wind tunnel tests reported in reference 3 and for hardware configurations in static rig performance and noise tests reported in reference 4.

TOGW	191 500 lb
Wing loading, W/S	84.0 psf
Wing thickness, t/c	$0.132_{outboard}$, 0.176_{SOB}
Wing sweep angle (0.25c)	25°
Wing aspect ratio, AR	7.5
Flap chord	0.26c
Wing thrust loading, $(T/S)_{un}$	32.2 psf
$SLST_{(un)}$, four engines at	18 300 lb
Engine fan pressure ratio	3.2
Wing nozzle pressure ratio	2.7
$\Delta P/P_F$	0.082
Peak noise at 500-ft sideline	90 PNdB

The updating process, results of which are described in subsequent sections, included:

- A minor revision in the bookkeeping of the engine installed performance and nozzle C_V (sec. 4.1)
- Revision of flow loss distribution in the air duct system to account for flow rig test results, and minor adjustments in duct sizes at several critical flow sections (sec. 4.2)
- Adjustment of basic thrust augmentation level and flow turning loss assumptions based on augmentor static rig tests accounting for nozzle and fairing geometry of the cruise blowing system (sec. 4.3)
- Revised estimate of augmentor acoustic performance, also based on augmentor static rig tests (sec. 4.3)

- Adjusted drag estimates for the cruise blowing nozzle system to reflect high-speed wind tunnel test results and a more detailed accounting for the installed nozzle configuration (sec. 4.4.2)

- Analysis of a higher aspect ratio wing (and related augmentor system) for the airplane and selection of the revised airplane configuration to satisfy the ground rules of the program (secs. 4.4.3, 4.4.4, and 4.4.5)

4.1 ENGINE PERFORMANCE

The engine cycle selected for the cruise blowing system was developed from the P&WA STF-395D engine by increasing the design fan pressure ratio to 3.2 using a Boeing cycle simulation. The resulting definition was designated STF-395D (BM-2), as described in reference 1.

The performance assumptions detailed in table I are unchanged from those of reference 1 except as given on the opposite page.

TABLE I.—PERFORMANCE ASSUMPTIONS FOR STF-395D (BM-2)

Parameter	Uninstalled	Installed	
		Sea level	Cruise altitude
Inlet recovery factor	1.0	0.97	0.99
Fan exit to fan nozzle, $\Delta P/P_F$	0.015		
Fan exit to wing duct wye, $\Delta P/P_F$		0.025	0.025
Wing duct wye inlet to nozzle, $\Delta P/P_F$		0.075	0.075
Power extraction, hp	0	225	50
Interstage compressor bleed, lb/sec	0	0.93	0.72
Secondary (augmentor) nozzle C_V	1.0	0.97[a]	0.97
Primary nozzle C_V	0.99	0.99	0.99

[a]C_V = 0.97 is applied in the calculation of the airplane takeoff thrust requirement. The sea level performance given in table II and figures 6 and 7 includes a wing nozzle reference C_V = 1.0.

- The augmentor nozzle C_V previously included in wing duct loss has been removed (see sec. 4.2). This aids bookkeeping by allowing the assignment of an adjusted overall blowing nozzle C_V rather than an incremental C_V.

- In reference 1, the wing duct pressure loss of 0.10 was assessed in addition to the fan air offtake duct pressure loss of 0.015, for an overall loss of 0.115. The updated performance includes an overall duct pressure loss of 0.10.

Table II gives the principal uninstalled and installed cycle characteristics for the STF-395D (BM-2) engine. The uninstalled SLS takeoff thrust corresponds to the thrust developed using the P&WA STF-395D advanced core of unit size.

TABLE II.—PERFORMANCE CHARACTERISTICS, STF-395D (BM-2) ENGINE CYCLE

Secondary airflow to wing, %	100
Uninstalled—SLS, standard day, takeoff	
Fan pressure ratio	3.2
Bypass ratio	2.11
Overall pressure ratio	25.6
Total thrust, lb	18 248
Total corrected airflow, lb/sec	441
Bare engine weight, lb	3185
Thrust weight, lb/lb	5.73
Thrust/airflow, lb/lb/sec	41.4
Bare engine length, in.	97.6
Fan tip diameter, in.	49.2
Installed—SLS, standard day, takeoff	
Total net thrust, lb	16 287
Thrust installation loss, %	10.7
Total actual airflow, lb/sec	418
Augmentor nozzle pressure ratio	2.71
Installed—100 kn, standard day, takeoff	
Primary nozzle ideal absolute jet velocity, fps	745
Augmentor nozzle ideal absolute jet velocity, fps	1516
Fan tip speed, fps	1440
Installed—30 000 ft, Mach 0.8, maximum cruise, 60% primary nozzle area	
Total net thrust, lb	4732
Thrust installation loss, %	11.1
Thrust lapse, $F_{N_{cr}}/F_{SLS_{un}}$	0.259
SFC, lb/hr/lb	0.824
SFC installation increase, %	7.1
SFC decrease for primary nozzle area change (100% -60%)	8.2
Max cruise TIT/sea level takeoff TIT	0.9

Figures 6, 7, and 8 present installed performance for the STF-395D (BM-2) cycle at takeoff, approach, and cruise, respectively.

4.2 AIR DISTRIBUTION SYSTEM PERFORMANCE

The cruise blowing duct system arrangement (drawing LO-DNS-222 for the wing aspect ratio, AR, of 7.5 and $t/c = 0.132_{outboard}$, $0.176_{side\ of\ body}$) was initially analyzed with estimated flow losses as described in reference 1. As a result of the duct flow rig tests reported in reference 5, it has been possible to assign lower loss coefficients to the engine-duct-to-wing-duct wye, but it was necessary to increase the coefficients assigned in the wing duct runs to account for losses attributed to local expansion in the vicinity of the individual nozzle air offtakes.

The wing nozzle velocity coefficient of reference 1 was comprised of an estimated factor 0.96 inherent in the variable portion of the duct loss, as derived from early flow rig tests, plus an additional factor 0.97 applied to account for assumed mixer nozzle geometry. Reassessment of the flow rig nozzle C_V showed that the estimated factor 0.96 included in the duct loss should more properly be 0.993. The $\Delta P/P_F$ equivalent of this thrust decrement ($\Delta P/P_F = 0.015$) was removed from the duct loss and the overall wing nozzle $C_V = 0.97$ was applied, representing the nozzles in the current updated performance.

The fixed portion of the duct loss represented by the engine fan duct and air offtake was adjusted from $\Delta P/P_F = 0.015$ to a more appropriate value of 0.025. The assignment of flow losses is graphically illustrated in figure 9 for the reference value, $\Delta P/P_F = 0.10$.

Figure 10 incorporates minor area adjustments made in critical sections of the LO-DNS-222 duct system to avoid excessive local velocities in operation up to overall $\Delta P/P_F = 0.12$. The wing upper surface contour shown in figure 10 is modified in the vicinity of the nozzles to illustrate the feasibility of area ruling without encroaching on duct volume.

The resulting nozzle area and thrust loading for the 7.5 aspect ratio wing are given in figure 11 as functions of duct loss, $\Delta P/P_F$, which serves as an index of the duct internal flow velocities. Variations in blowing nozzle area and thrust loading with wing aspect ratio are given in figure 12.

4.3 AUGMENTOR THRUST AND NOISE PERFORMANCE

The preferred flap concept of reference 1 (LO-DNS-223), together with the equivalent slot nozzle height of 1.36 in. ($A_A/S = 0.617$ sq in./sq ft) in figure 10, for a flap chord of 0.26c yields an

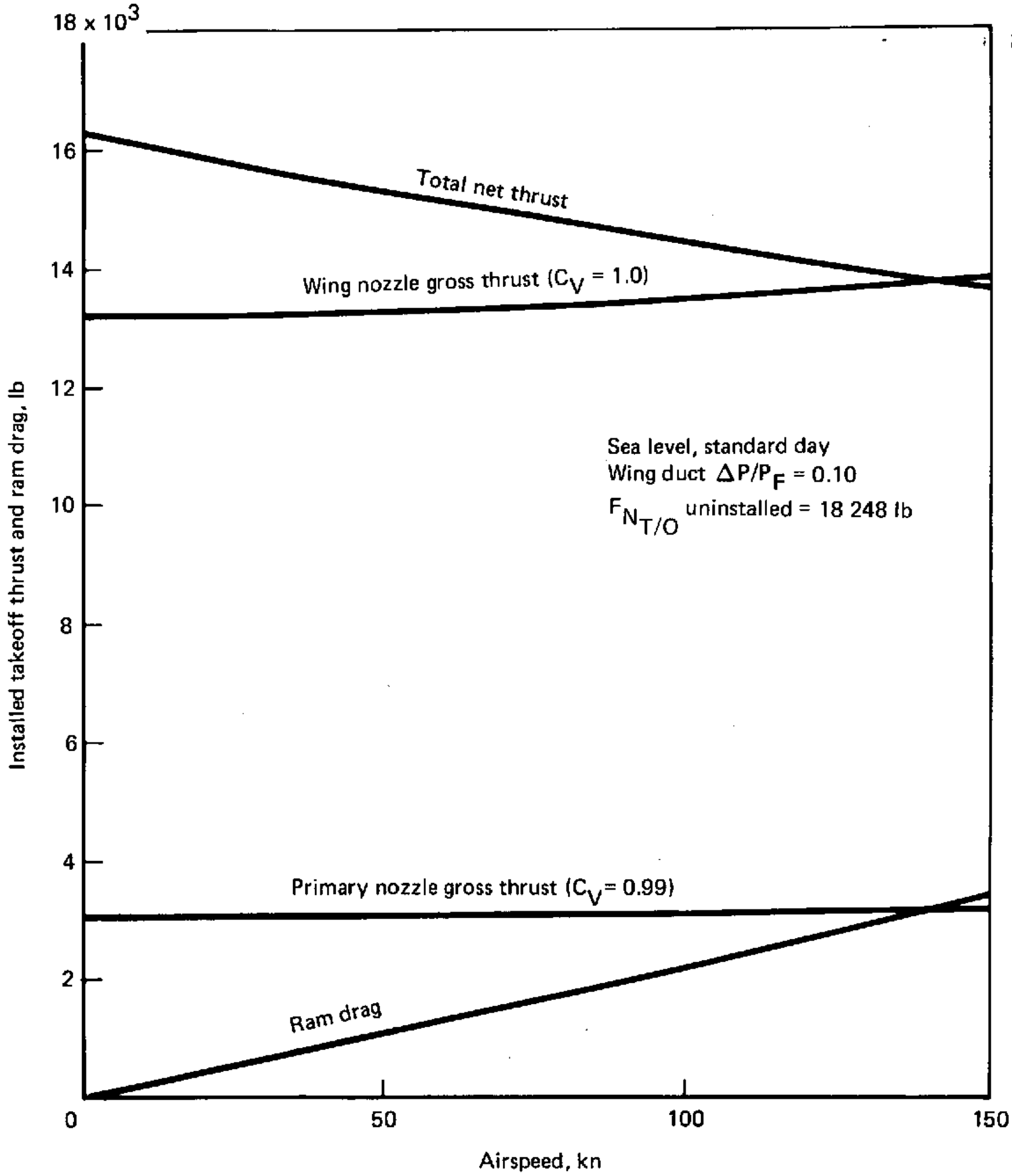


FIGURE 6.–STF-395D (BM-2) INSTALLED TAKEOFF PERFORMANCE

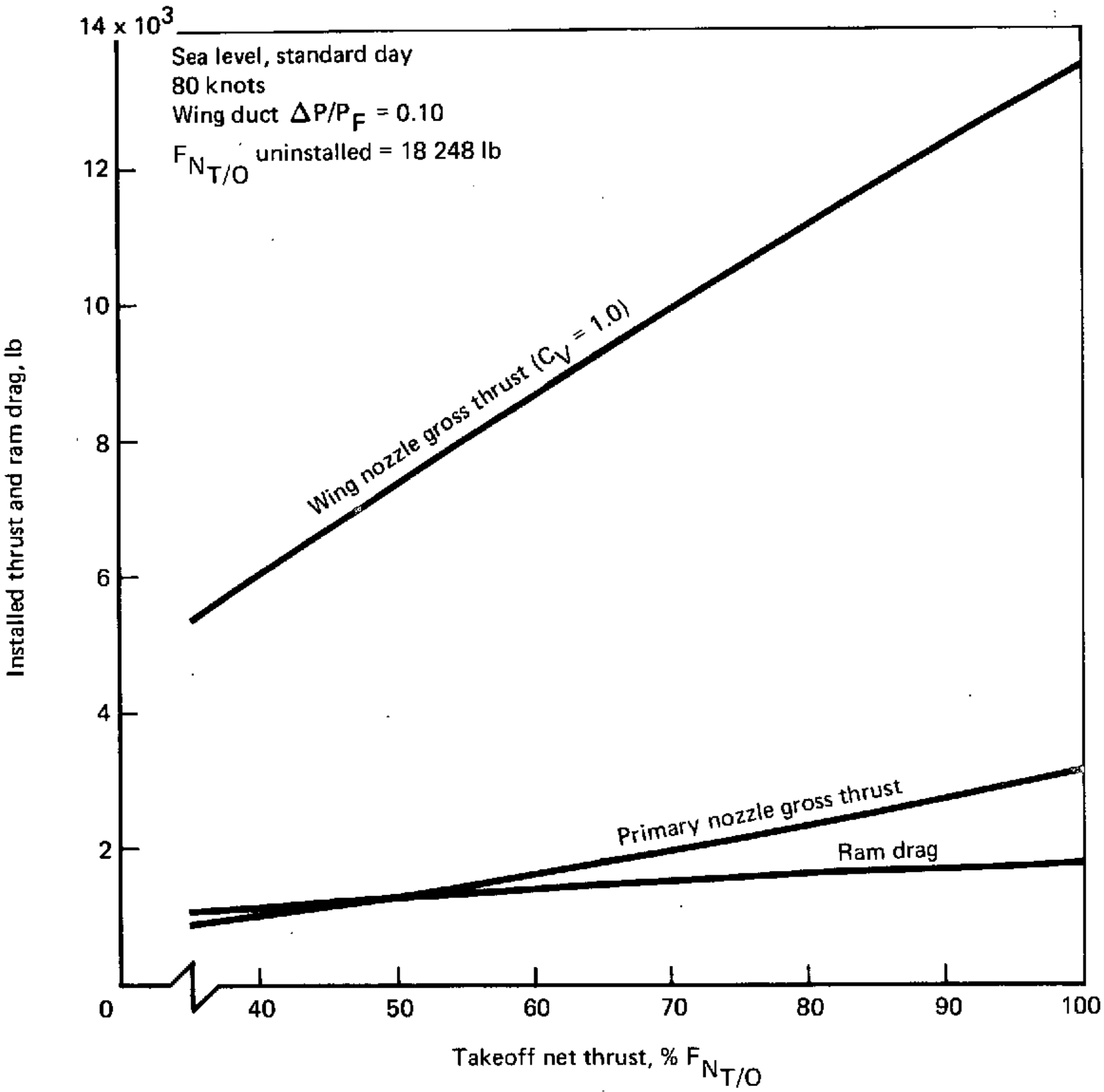


FIGURE 7.—STF-395D (BM-2) INSTALLED APPROACH PERFORMANCE

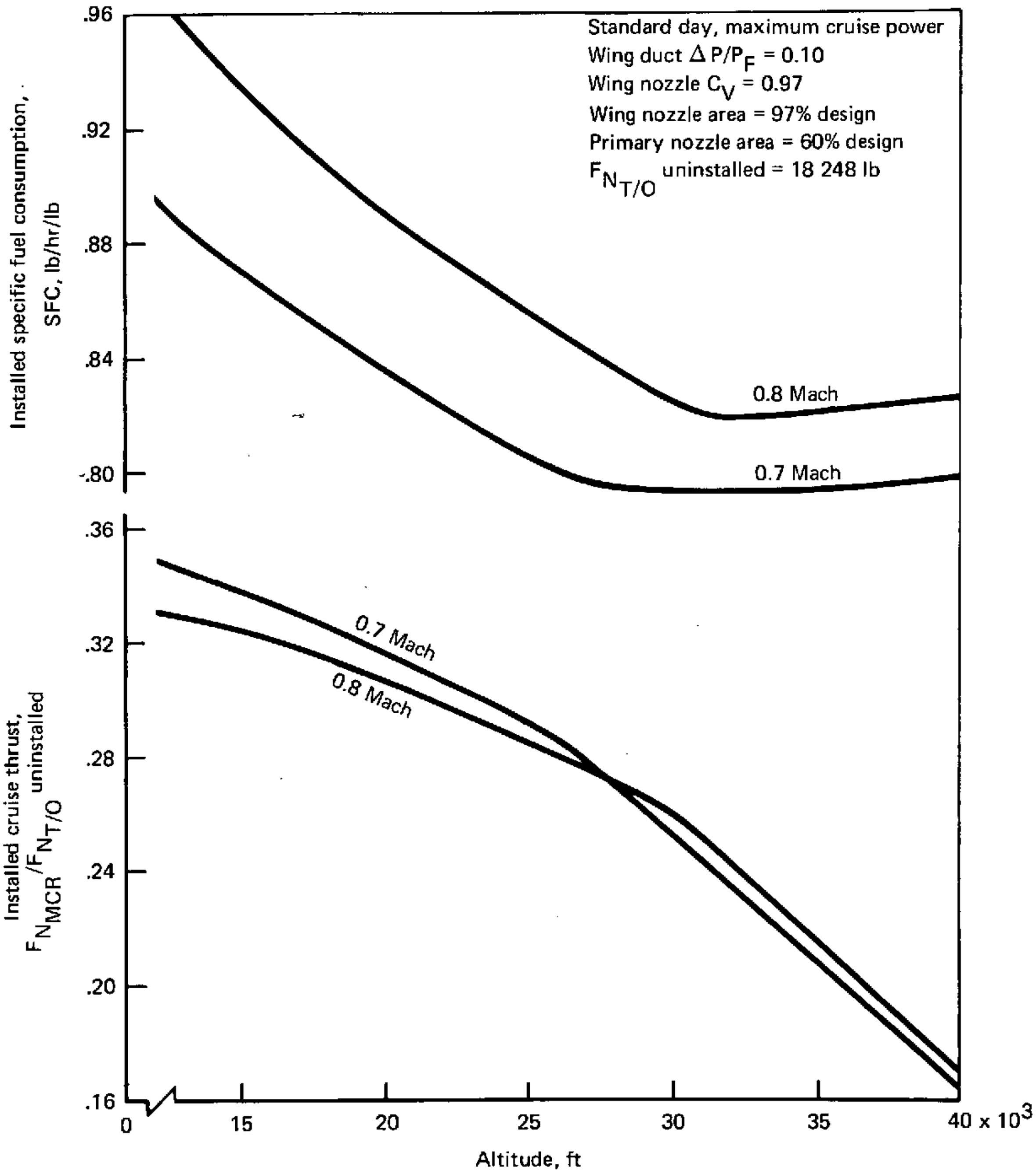


FIGURE 8.—STF-395D (BM-2) INSTALLED CRUISE PERFORMANCE

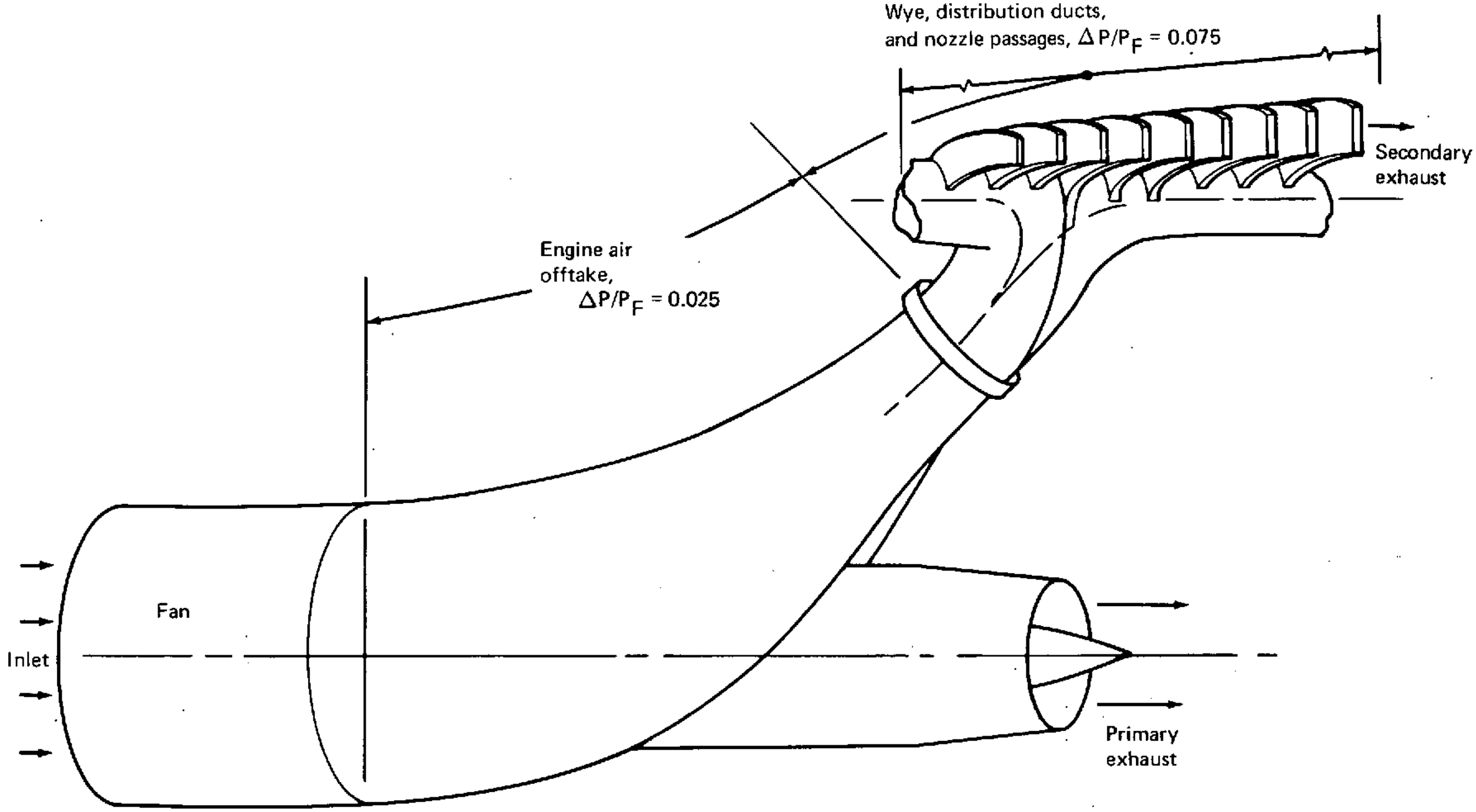


FIGURE 9.—ASSIGNMENT OF AIR DUCT FLOW LOSSES

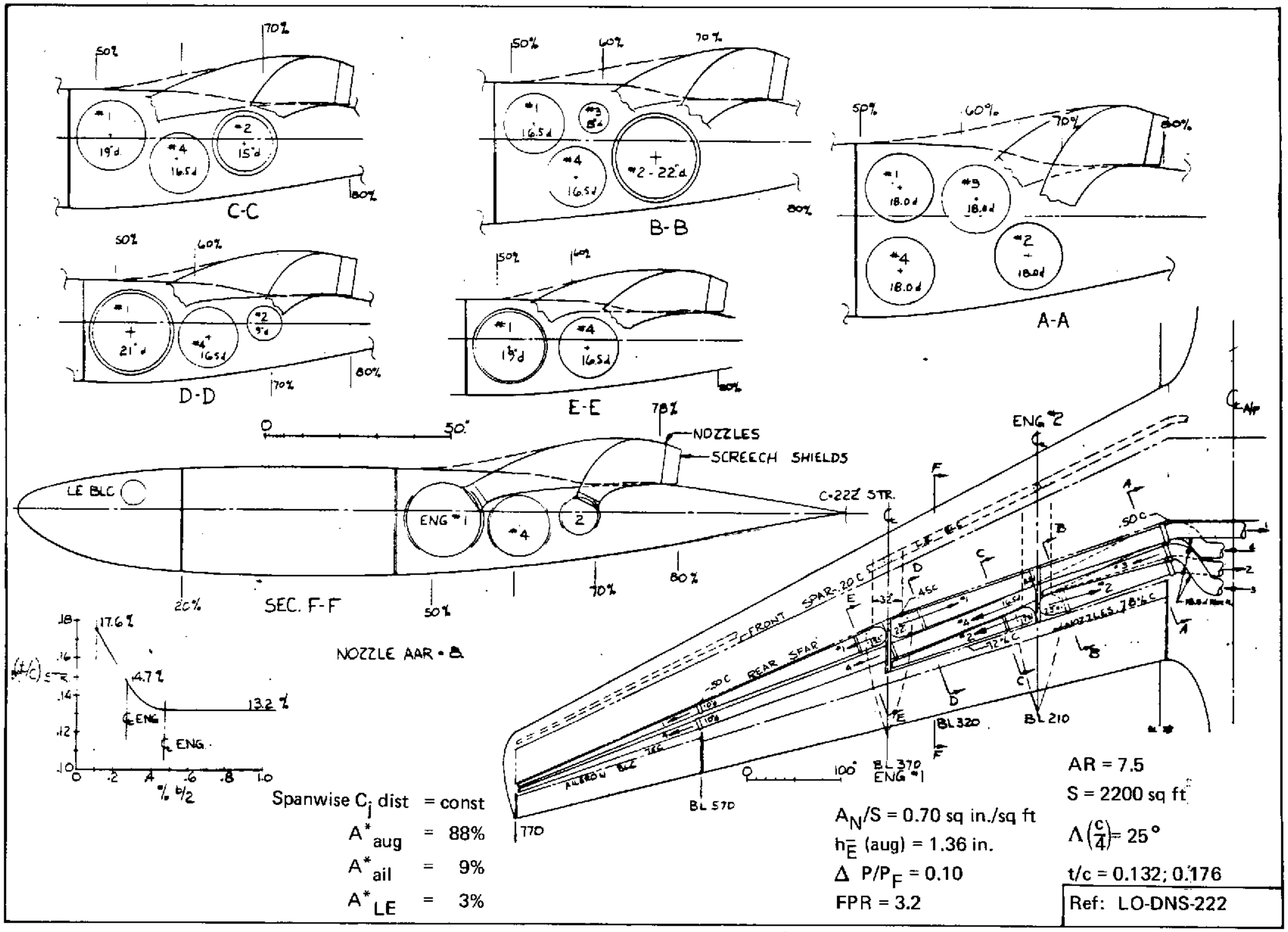


FIGURE 10.—AIR DISTRIBUTION DUCT ARRANGEMENT, AUGMENTOR WING CRUISE BLOWING VALVELESS SYSTEM

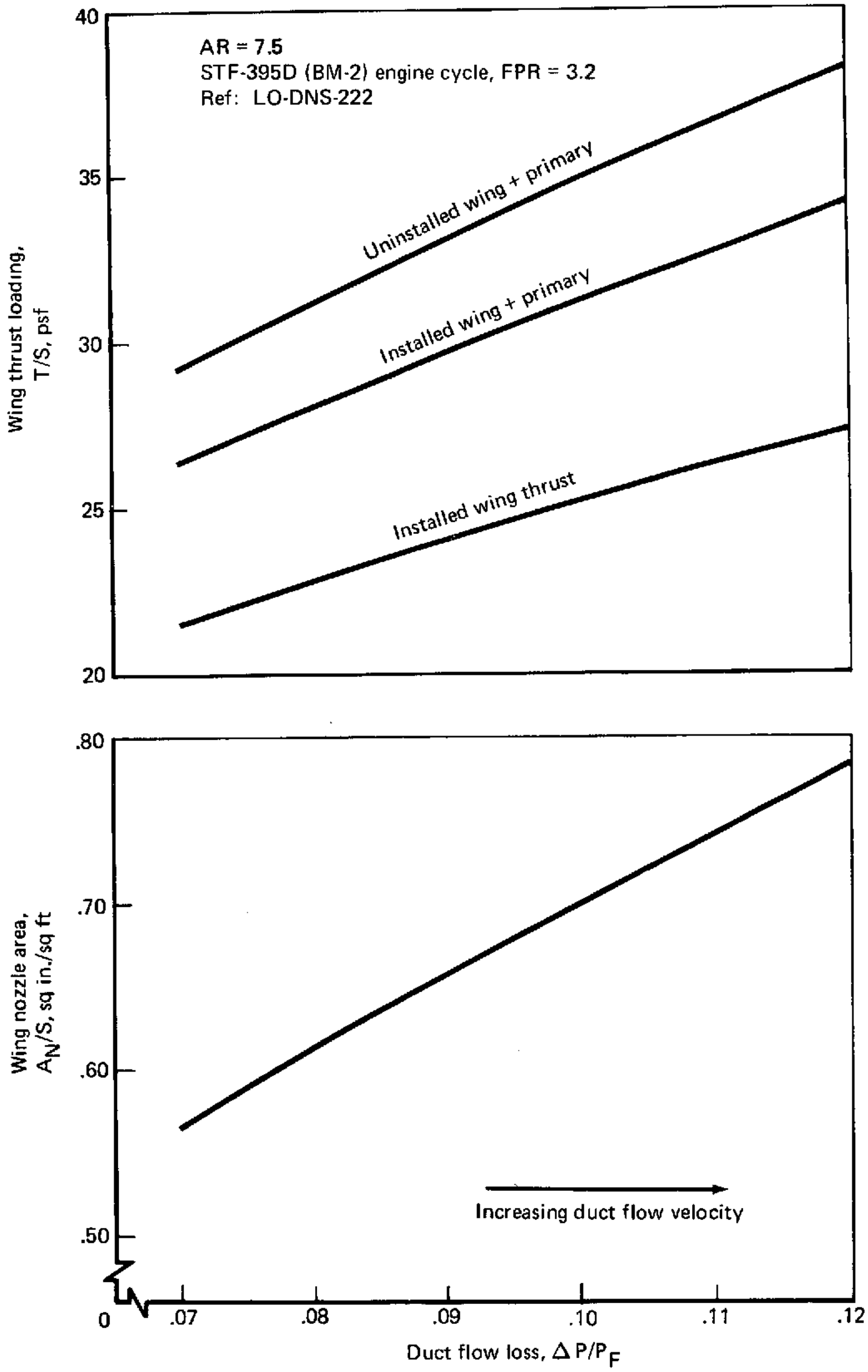


FIGURE 11.–WING NOZZLE AREA AND THRUST LOADING AS FUNCTIONS OF DUCT FLOW LOSS

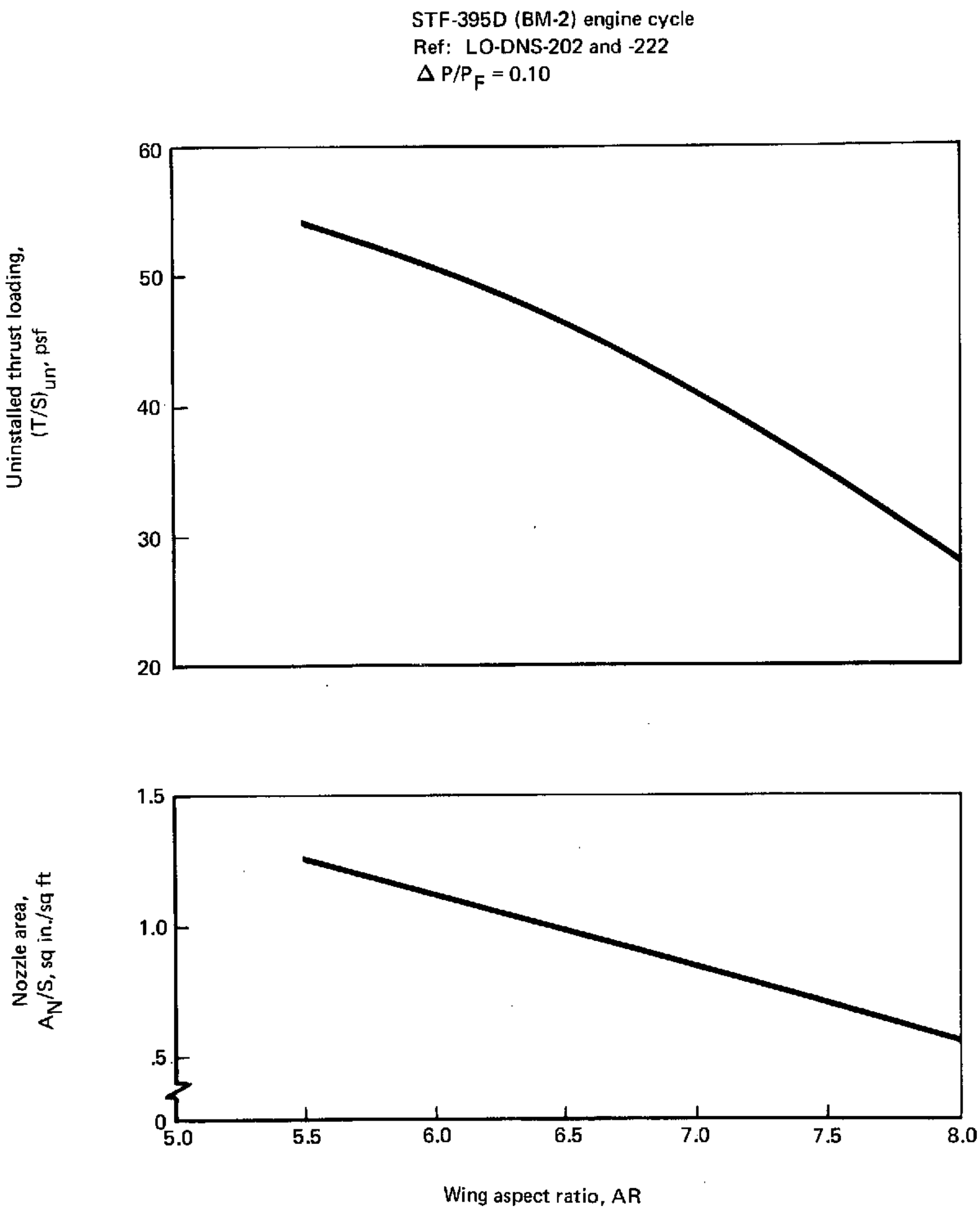


FIGURE 12.–WING NOZZLE AREA AND THRUST LOADING AS FUNCTIONS OF WING ASPECT RATIO

augmentor length ratio, $L/h_{\bar{E}}$, of 42.5 compared with 46 in reference 1 (see fig. 13). As this adversely affects both the thrust and noise performance of the augmentor, the physical arrangement was reviewed. With some compromise in flap contour, as indicated in figure 14, the flap chord may be increased to 0.28c, restoring the $L/h_{\bar{E}}$ factor to 46. While this change would imply a compromise in flap structural thickness as well as a considerable revision in the actuating linkage concept, it is recognized that these elements are necessarily the subject of wind tunnel and design development in a continuing program.

Static thrust augmentation characteristics and adjustment factors to account for flow turning relative to the nozzle, acoustic lining friction loss, nozzle spacing, and nozzle pressure ratio are given in figures 15, 16, and 17. These data are derived from the static rig tests of reference 4.

The relationship derived in reference 4 between the acoustic data base and the geometry of the augmentor in the airplane is presented in figure 18. The solid lines represent acoustic performance of augmentors having nozzle array ratios of 6.0 and 8.0, an equivalent slot nozzle aspect ratio of 100:1, and a flap length ratio, $L/h_{\bar{E}}$ of 55. The noise levels with the 100:1 slot are projected to the 500-ft sideline for airplane takeoff conditions and are plotted for a range of equivalent slot nozzle heights. The range of nozzle height is selected to encompass the requirements of the cruise blowing duct system in the reference 2200-sq-ft wings, with aspect ratios of 7.5 and 8.0 operating at $\Delta P/P_F$ from 0.08 to 0.12.

The broken lines in figure 18 adjust the acoustic performance of the nozzle array ratio 6.0 and 8.0 augmentors from constant $L/h_{\bar{E}} = 55$ to the augmentor geometry of 2200-sq-ft wings of aspect ratios 7.5 and 8.0 and flap chords of 0.26c and 0.28c. In these adjusted curves, the $L/h_{\bar{E}}$ varies with:

- Wing aspect ratio and flap configuration
- Equivalent slot height, which is a function of wing aspect ratio, duct configuration, and duct loss

As the curve indicates, the nozzle array area ratio of 8.0 does not meet the 90-PNdB noise goal except in the wing of aspect ratio 8.0. Nozzle array ratio 6.0 provides substantial margin in the aspect ratio 8.0 wing and, with the 0.28c flap chord, is acceptable up to $\Delta P/P_F = 0.10$ in the 7.5 aspect ratio wing.

Figure 2 relates thrust augmentation (derived by application of figs. 13, 15, 16, and 17) and sideline noise of the augmentor to the airplane sizing parameter—wing thrust loading, $(T/S)_{un}$—in terms of wing aspect ratio and duct system pressure loss, $\Delta P/P_F$, for the nozzle array ratio = 6.0 and flap chord = 0.28c.

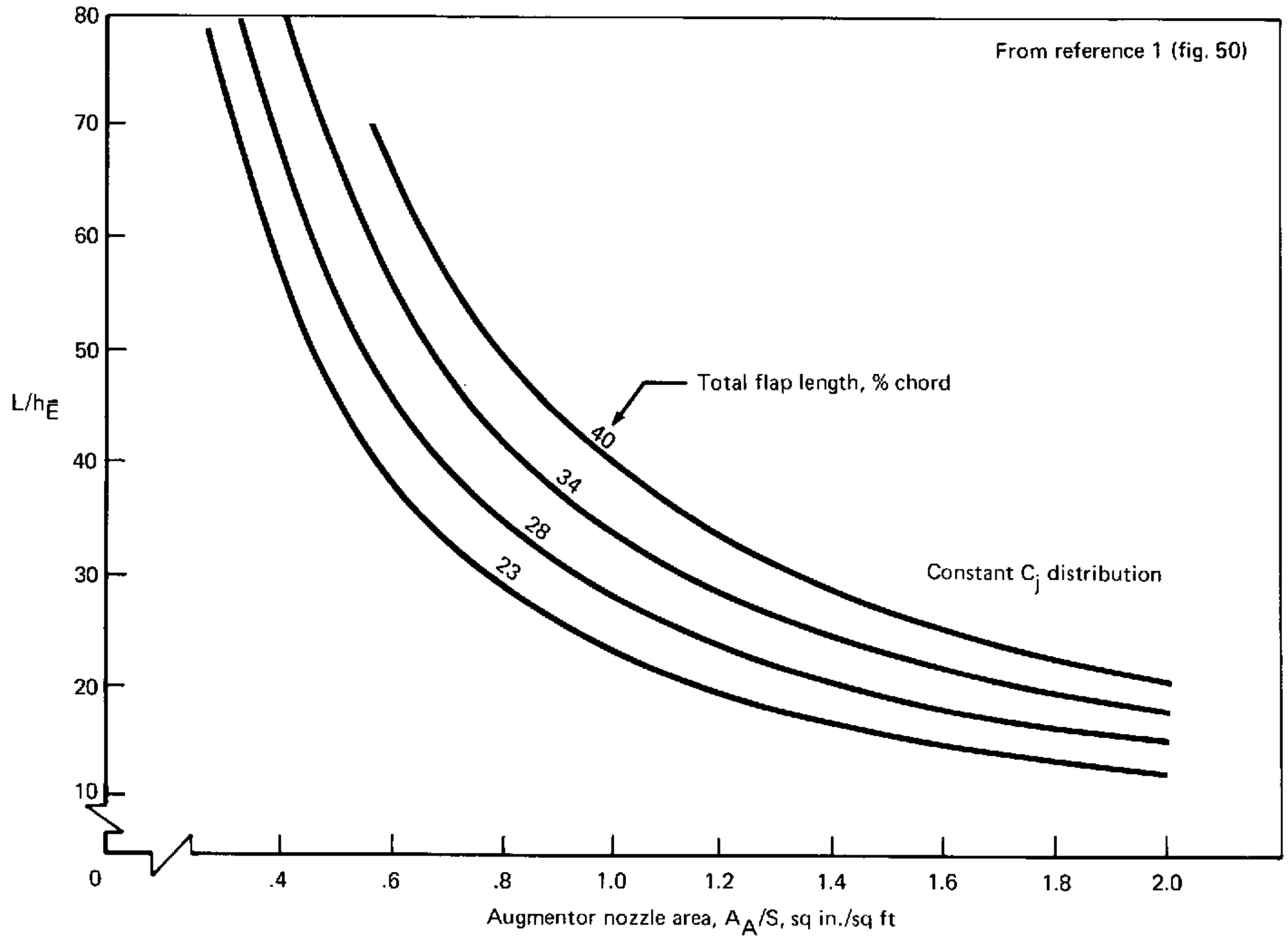


FIGURE 13.—RATIO OF FLAP LENGTH TO EQUIVALENT NOZZLE HEIGHT AS A FUNCTION OF NOZZLE AREA AND FLAP CHORD

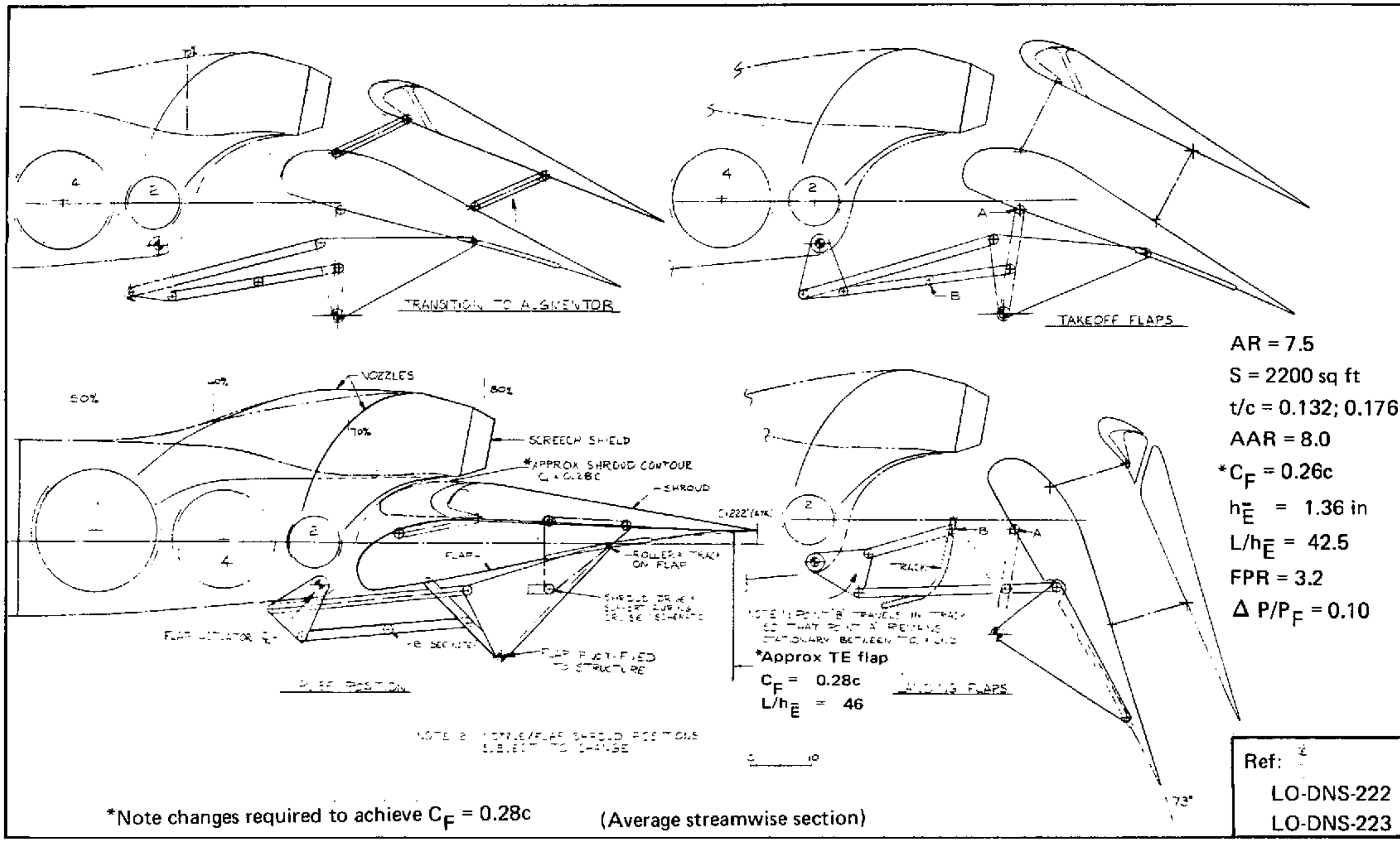


FIGURE 14.—AUGMENTOR WING CRUISE BLOWING FLAP CONCEPT

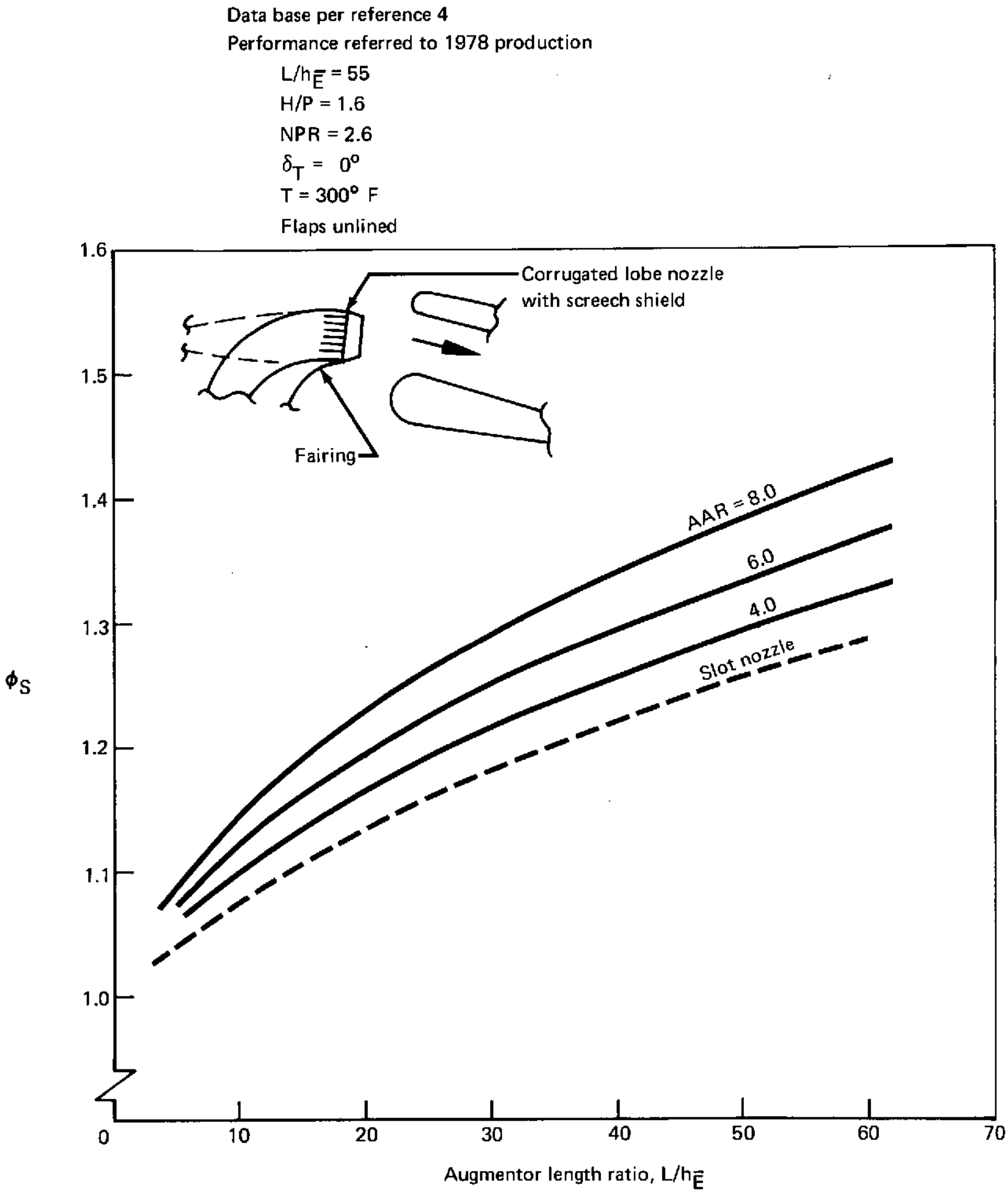


FIGURE 15.—STATIC THRUST AUGMENTATION AS A FUNCTION OF AUGMENTOR LENGTH AND NOZZLE ARRAY AREA

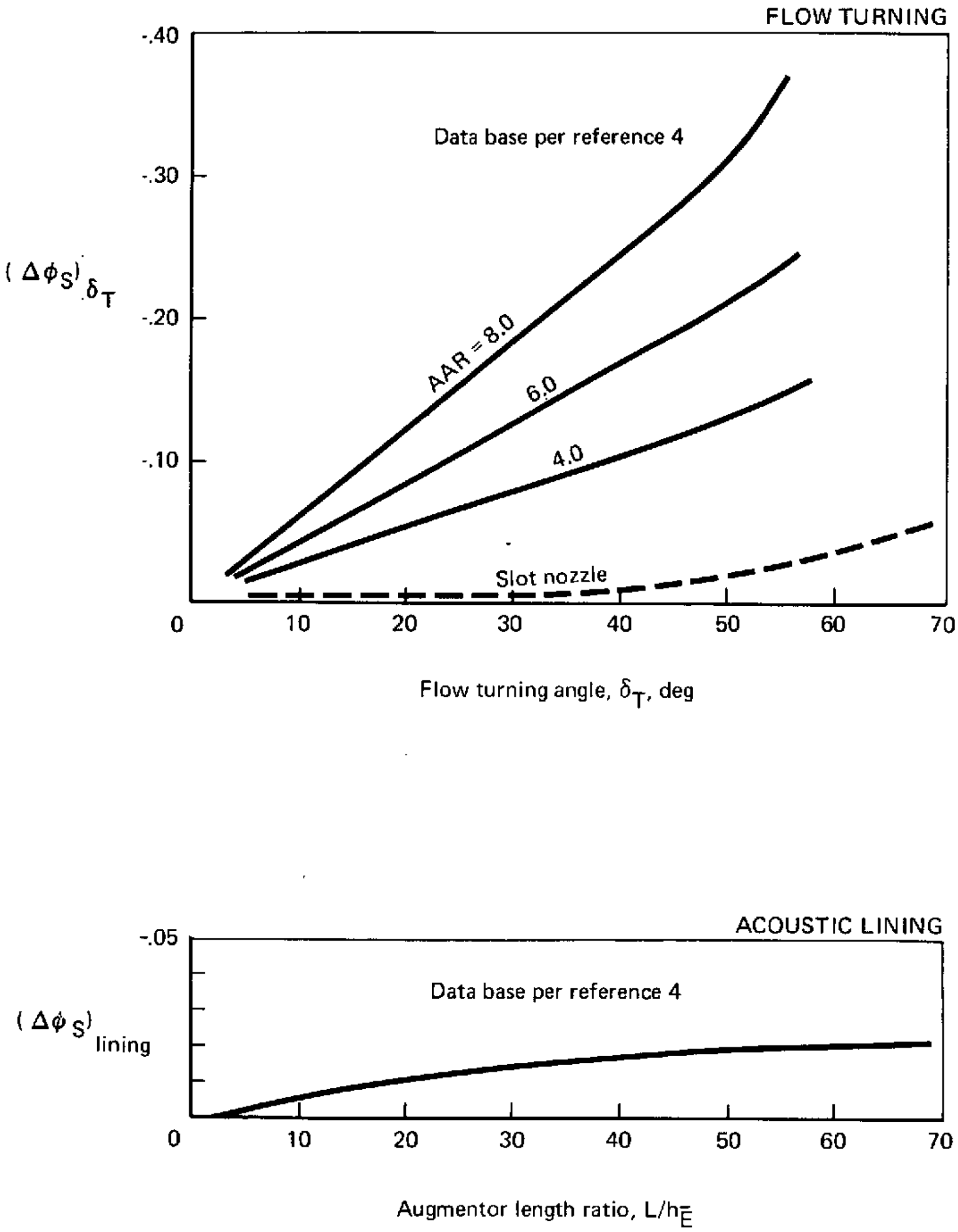
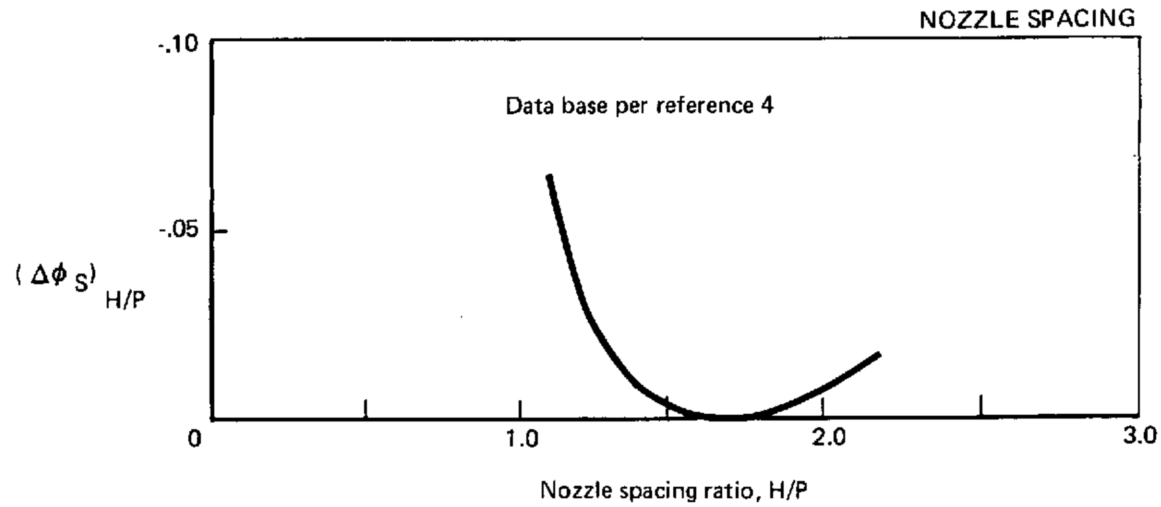


FIGURE 16.—ADJUSTMENTS TO STATIC THRUST AUGMENTATION TO ACCOUNT FOR FLOW TURNING AND ACOUSTIC LINING



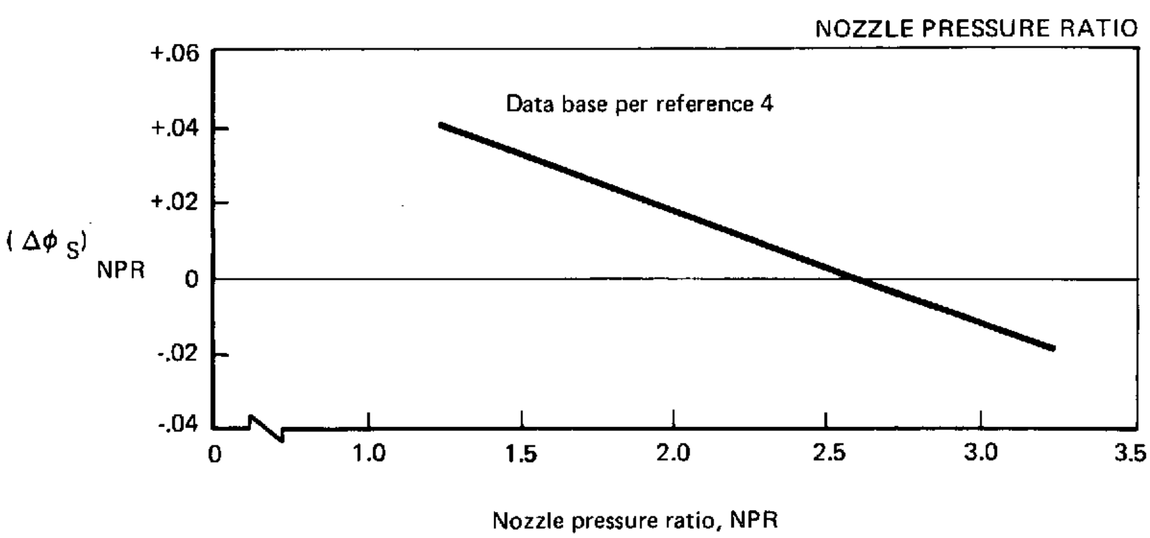


FIGURE 17.—ADJUSTMENTS TO STATIC THRUST AUGMENTATION TO ACCOUNT FOR NOZZLE SPACING AND PRESSURE RATIO

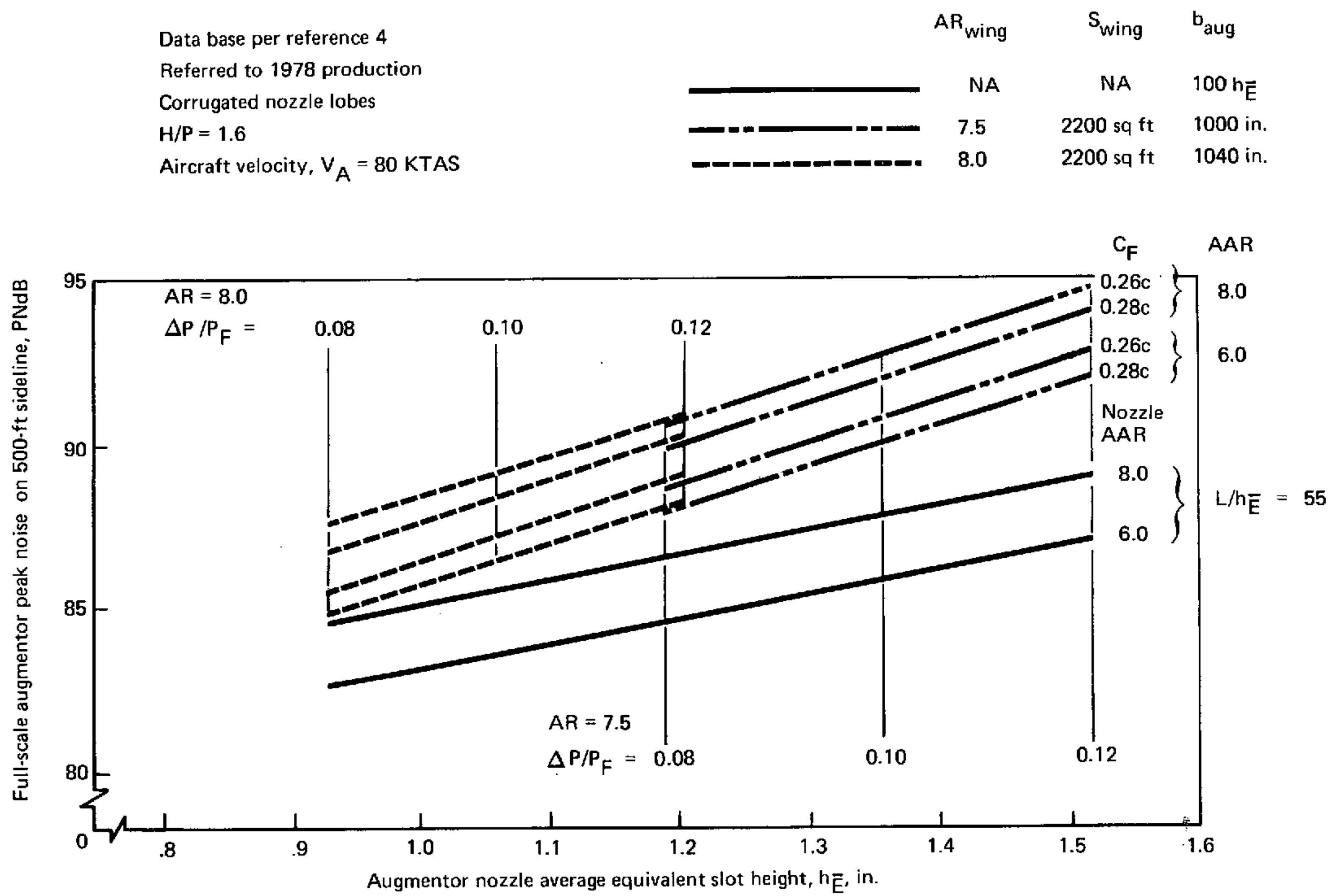


FIGURE 18.—AUGMENTOR NOISE AS A FUNCTION OF NOZZLE GEOMETRY AND FLAP LENGTH

The design point at aspect ratio = 7.5 and $\Delta P/P_F$ = 0.10 was selected as discussed in section 4.4 to achieve the airplane goal of 90-PNdB peak noise on the 500-ft sideline. Table III compares the augmentor performance characteristics of the selected point with that identified in reference 2. The major difference is the lower augmentation ratio, ϕ_S, which is the consequence of the nozzle array ratio selection of 6.0 versus 8.0 used in reference 2, as well as a lower basic level of augmentation and a greater flow turning loss established in static tests of the cruise blowing system. Those test results are discussed in reference 4.

TABLE III.—COMPARISON OF AUGMENTOR CHARACTERISTICS

Parameter	Ref. 1, page 71	Update
Fan air to wing, %	100	100
Wing aspect ratio	7.5	7.5
t/c	$0.132_{outboard}$, 0.176_{SOB}	$0.132_{outboard}$, 0.176_{SOB}
FPR	3.2	3.2
$\Delta P/P_F$	0.082	0.10
A_N/S, sq in./sq ft	0.64	0.70
A_{aug}/S	0.56	0.62
C_F	0.26c	0.28c
δ_F, deg	35	30
δ_T, deg	27	22
L/h_E	46.0	46.0
Nozzle AAR	8.0	6.0
ϕ_S[a]	1.42	1.31
$\Delta\phi$ turning	-0.08	-0.09
$\Delta\phi$ lining	-0.04	-0.02
$\Delta\phi$ NPR	0	0
$\Delta\phi$ static	1.30	1.20

[a] Referred to 1978 production ($\Delta\phi$ = +0.05)

Since the wing area of the final sized airplane is 2309 sq ft, the augmentor nozzle equivalent slot geometry differs slightly (slot length = +2.8%, slot height = +2.2%) from the geometry of the 2200-sq-ft wing in figure 2. This indicates an adverse effect of about one-quarter PNdB in the predicted noise of the augmentor, which may be offset by a small increase in wing aspect ratio. This noise increase was not regarded as sufficiently significant to warrant another iteration in the aircraft sizing cycle.

The estimated peak sideline noise for the airplane of the selected design point is summarized in figure 19.

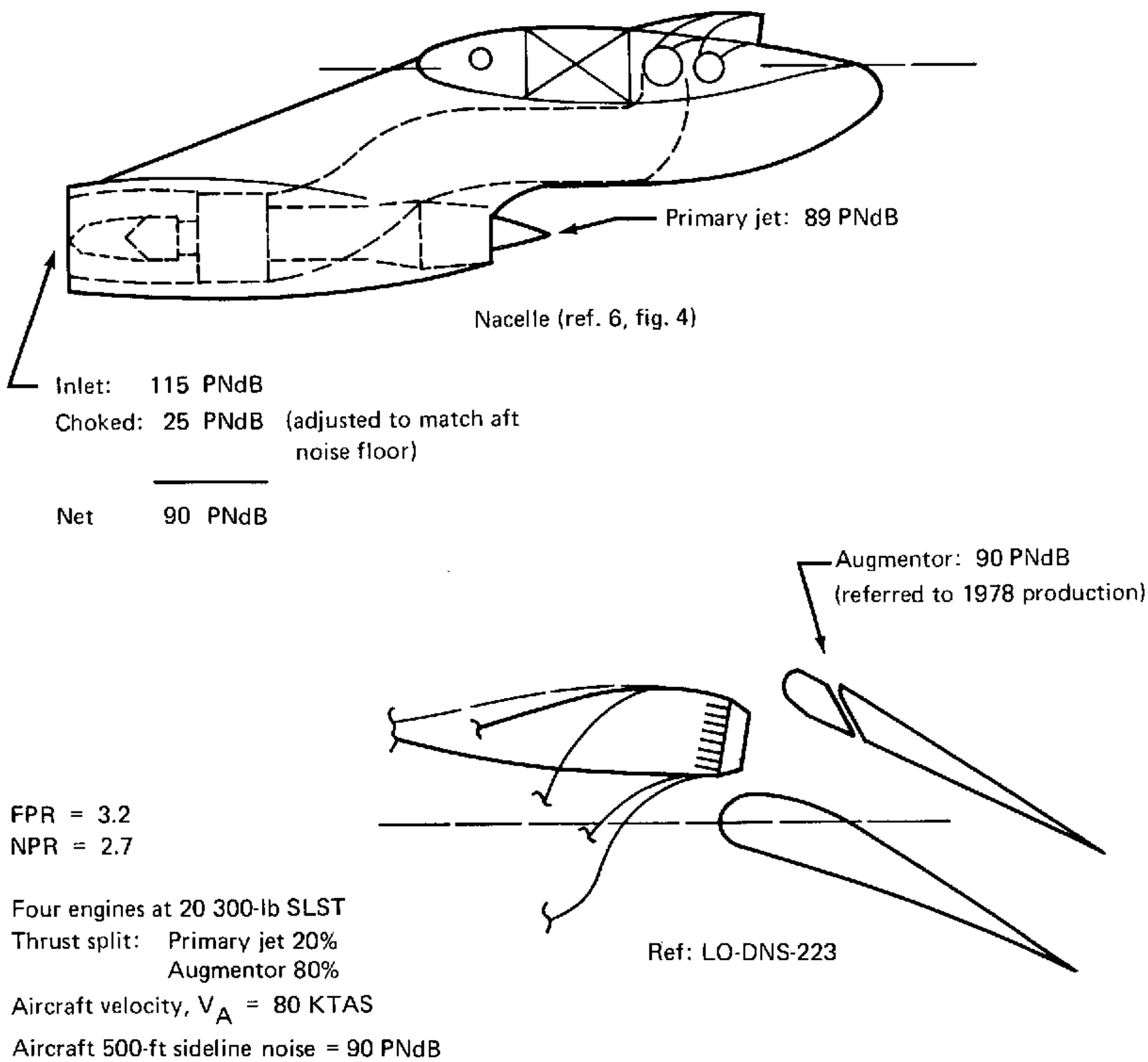


FIGURE 19.—ESTIMATED AIRPLANE TAKEOFF NOISE—500-FT SIDELINE, AUGMENTOR WING CRUISE BLOWING VALVELESS SYSTEM

4.4 AUGMENTOR WING AIRPLANE INTEGRATION

The selected airplane design of reference 1 has been refined to incorporate the results of the augmentor and duct system static tests of references 4 and 5, as well as the high-speed wind tunnel tests of cruise blowing nozzle drag reported in reference 3.

4.4.1 Augmentor Performance

Low-speed performance is based on the 40- by 80-ft wind tunnel tests of a swept wing augmentor (Working Paper 271, NASA-Ames, April 1971, TM X-62029). These data were modified to reflect airplane differences in wing planform, flap chord, leading edge blowing, and nozzle C_V. The static augmentation levels were developed from the static tests of reference 4 modified for flap chord, thrust loading, flow turning angle, lining effects, and nozzle design, as explained in section 4.3. Augmentor thrust lapse with velocity was accounted for by assuming that gross thrust was reduced by the effects of augmentor inlet losses of $(\Delta P_T/q)_{inlet} = 0.10$ and diffuser losses of $(\Delta P_T/q)_{diff} = 0.10$ and by using a theoretical momentum drag term based on augmentor secondary mass flow. The resulting lapse rate as a function of static augmentation ratio is shown in figure 20.

4.4.2 Cruise Blowing Nozzle Drag

Transonic wind tunnel tests of a quasi-2D model (ref. 3), representing a wing section of an airplane with cruise blowing nozzles of AAR = 8.0 and $A_N/S = 0.64$, determined that the parasitic sectional drag increase due to the nozzles was $\Delta C_d = 0.0030$. An additional sectional drag increase of $\Delta C_d = 0.0007$ at $C_j = 0.044$ was attributed to scrubbing of the wing aft of the nozzles by the jet efflux.

Figure 21 shows total (parasite and scrubbing) nozzle drag as a function of nozzle area and configuration. These data were derived from the reference 3 test data correcting from sectional to wing area and adjusting for changes in wetted area and Reynolds number.

The drag of the AAR = 8.0, $A_N/S = 0.64$ nozzles used on the selected airplane of reference 1 is shown in figure 21 as $\Delta C_D = 0.0025$, approximately double the $\Delta C_D = 0.0012$ used in the reference 1 calculations that assumed much less wetted area (shorter nozzle fairings). The nozzle fairings were extended forward to the 50% chord location on the test model to reduce the risk of premature drag rise. Since basic skin friction drag of the model nozzles is calculated to be ΔC_d = 0.00256 (or 85% of the nozzle parasitic drag) and no drag rise was caused by the nozzles, future testing may show that nozzle drag could be decreased by shortening the fairing to reduce wetted area.

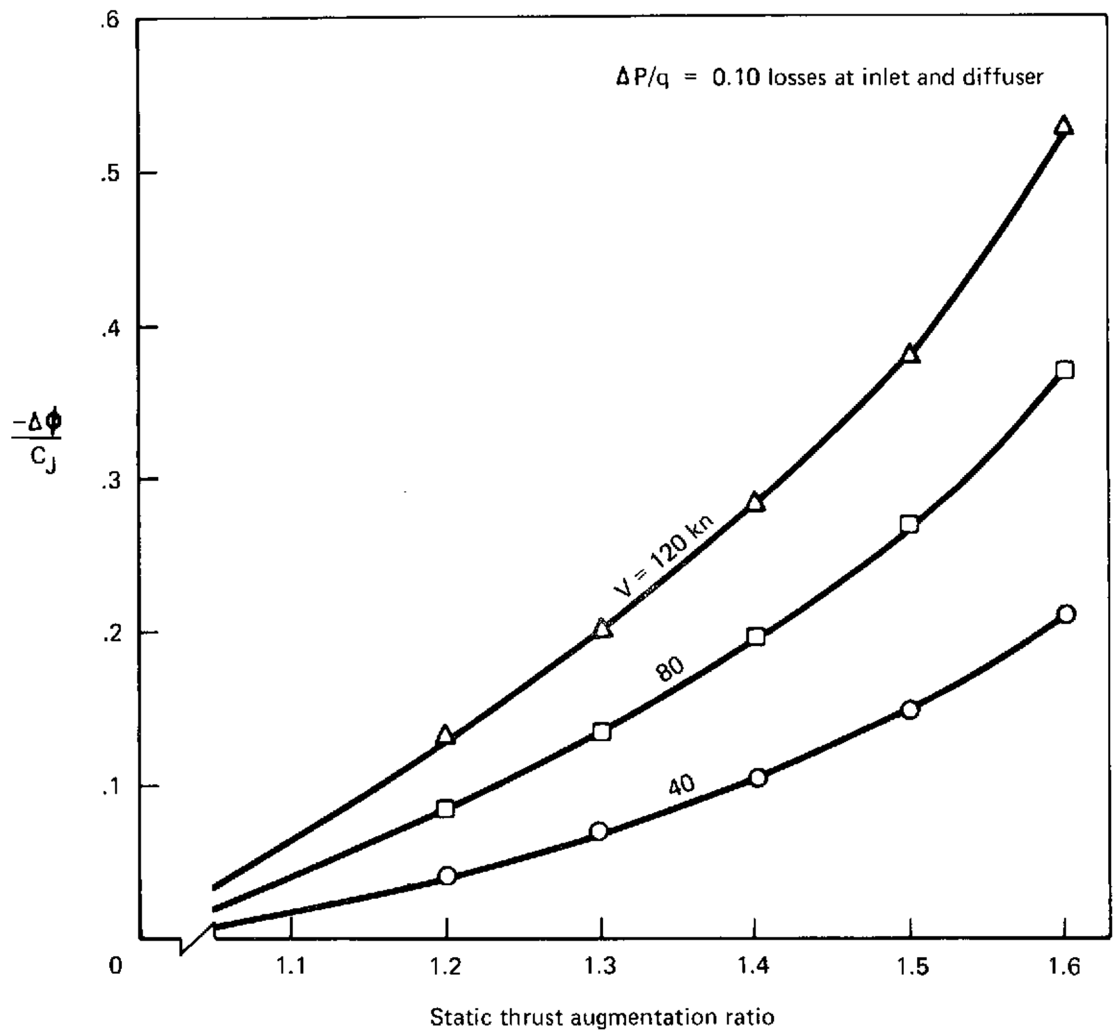


FIGURE 20.—AUGMENTOR THRUST LAPSE

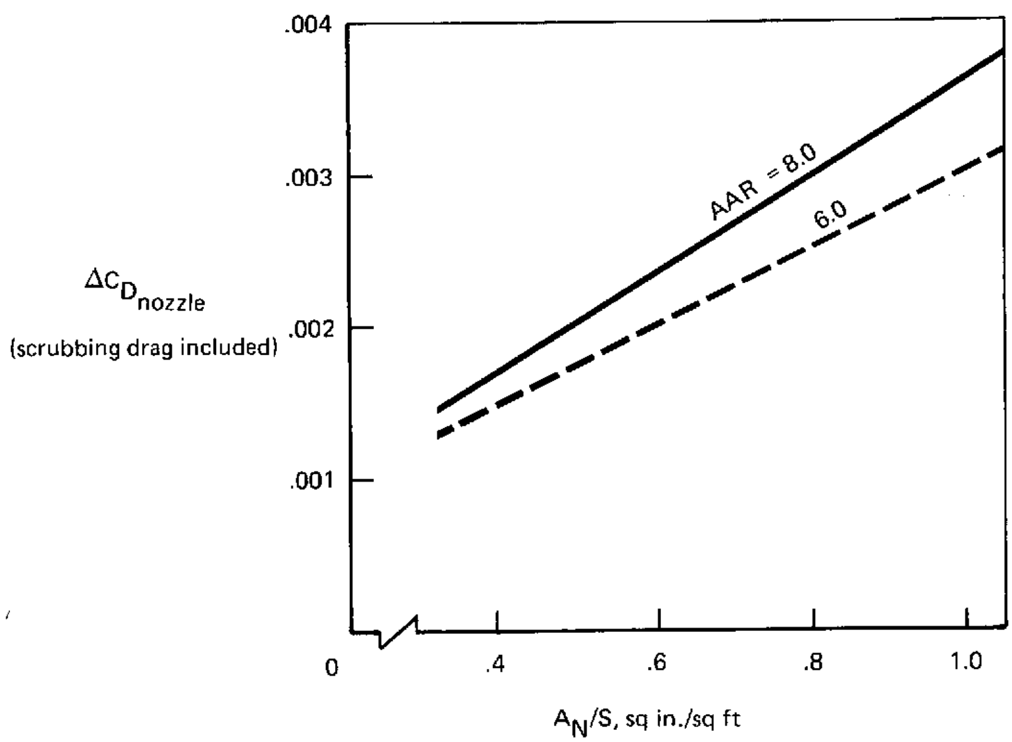


FIGURE 21.—CRUISE BLOWING NOZZLE DRAG

4.4.3 Refining the Task VII Configuration

The selected configuration of reference 1 is updated to incorporate new information on augmentation, nozzle and duct system weights, duct system losses, nozzle configuration, and nozzle drag. The major changes are:

- Static augmentation lowered. The test data of the reference 4 configuration with nozzles mounted on the wing upper surface demonstrated lower basic augmentation and higher turning losses than assumed in reference 1.
- Duct system weight of base configuration reduced 690 lb by weight reevaluation.
- Takeoff thrust increased by 0.5%, cruise thrust increased by 0.6%, and SFC reduced by 0.6% by elimination of a $\Delta P/P = 0.015$ carried in the wing thrust of the installed engine data of reference 1.
- Nozzle array area ratio changed from 8.0 to 6.0 to reduce noise. This increases nozzle weight by 270 lb but reduces nozzle drag by $\Delta C_D = 0.0004$.
- Augmentor flap chord increased from 0.26c to 0.28c to reduce noise and improve augmentation.

4.4.4 Effect of Wing Planform and Duct Flow Velocity

Augmentor noise and performance is a strong function of the ratio of flap chord to nozzle area (L/h_E). L/h_E is determined by the thrust loading established by duct flow capacity and wing planform. Wing aspect ratio and duct flow velocity are the prime variables in determining the tradeoffs between noise and TOGW for a given engine and augmentor system.

Figure 22 shows that with AR = 8.0 and duct flow velocity corresponding to $\Delta P/P = 0.10$, the thrust and wing loading is established by the intersection of the duct volume limit and M = 0.80 at the 30 000-ft CTOL initial cruise thrust requirement. The resulting T/W = 0.412 and unacceptably low W/S = 68.1 give takeoff performance better than the 2000-ft STOL takeoff field length requirement, and the L/h_E of 56.9 reduces noise to 86.5 PNdB. However, the 227 700-lb TOGW is about 30 000 lb greater than if the duct flow capacity could be increased to match the CTOL cruise and STOL thrust requirements at T/W = 0.39 and W/S = 81.

The effect of increasing duct flow velocity to that associated with $\Delta P/P = 0.12$ is shown in figure 23 for AR = 8.0. This design is also sized by the CTOL cruise thrust requirement at a wing loading lower than that required for the STOL takeoff. The smaller wing allowed by the greater duct flow capacity has reduced TOGW to 205 300 lb, a 22 300-lb weight saving from the $\Delta P/P = 0.10$ airplane. The smaller flap chord has reduced L/h_E to 50.9 and increased noise to 88 PNdB.

Decreasing wing aspect ratio increases the wing volume available for ducts and thus raises the allowable thrust loading for a given duct flow velocity. Figure 24 shows that with duct flow velocity for $\Delta P/P = 0.12$ and AR = 7.5, the airplane is sized by the interaction of the CTOL fuel volume requirement and the duct volume limit at T/W = 0.435 and W/S = 87.6. The higher wing loading of the AR = 7.5 airplane has reduced TOGW to 198 000 lb, a weight savings of 7300 lb compared to the AR = 8.0 airplane at the same duct flow velocity. L/h_E has decreased to 41.6 and noise has increased to 92 PNdB because of the greater nozzle area and smaller flap area at the higher thrust loading. Takeoff performance is better than the 2000-ft TOFL requirement.

Reducing the duct flow velocity of the AR = 7.5 airplane to correspond to duct pressure losses of $\Delta P/P = 0.10$ reduces the available wing thrust loading, T/S, and the larger wing exceeds the CTOL fuel volume requirements. Figure 25 shows that the design point T/W = 0.413, and W/S = 84.4, as determined by the 2000-ft TOFL, meets all mission criteria. The lower thrust loading has increased L/h_E to 45.8 and lowered noise to the 90-PNdB goal. TOGW is 195 800 lb, or 2200 lb lighter than the AR = 7.5, $\Delta P/P = 0.12$ design.

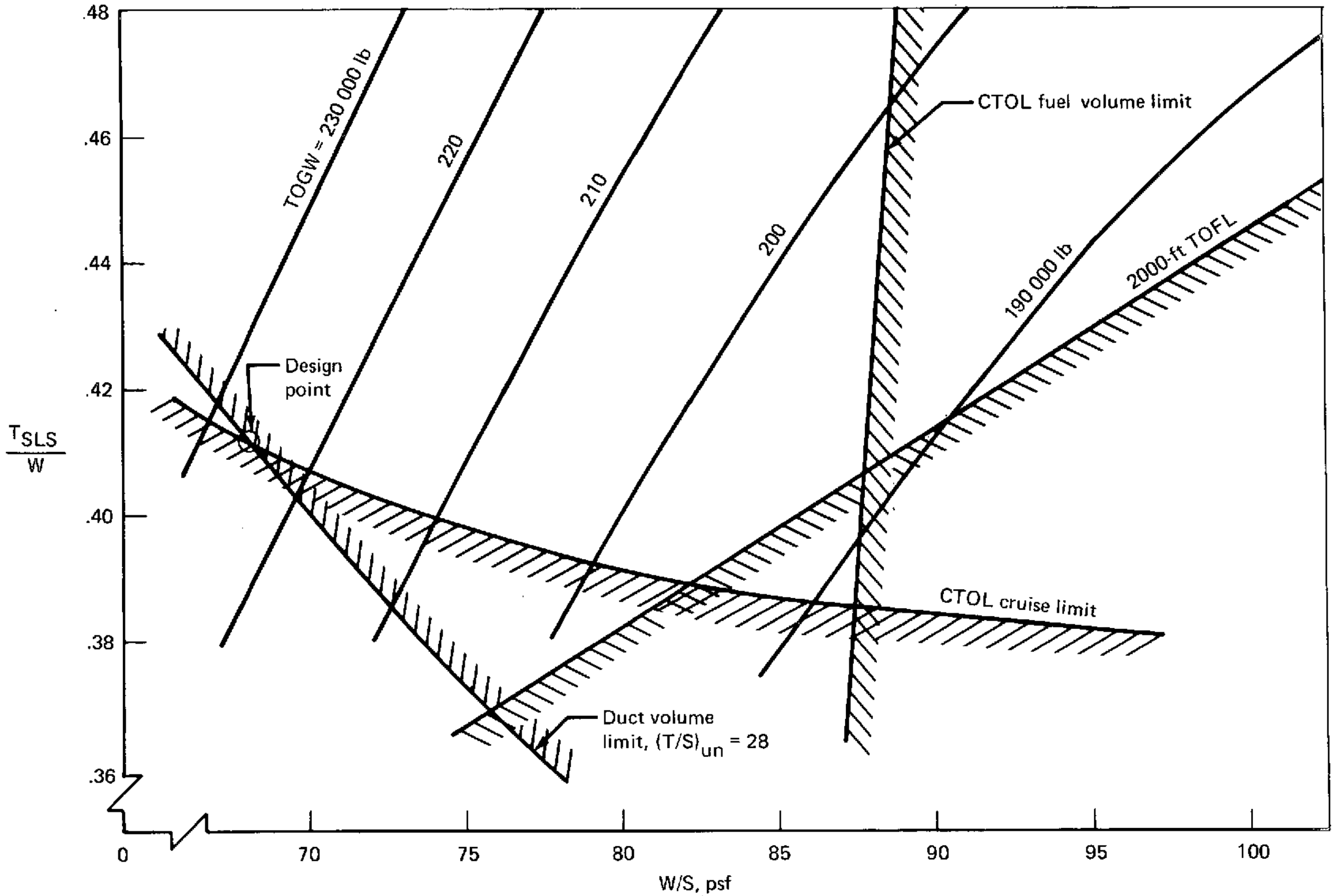


FIGURE 22.—AUGMENTOR WING AIRPLANE SIZING PARAMETERS
(AR = 8.0, ΔP/P = 0.10)

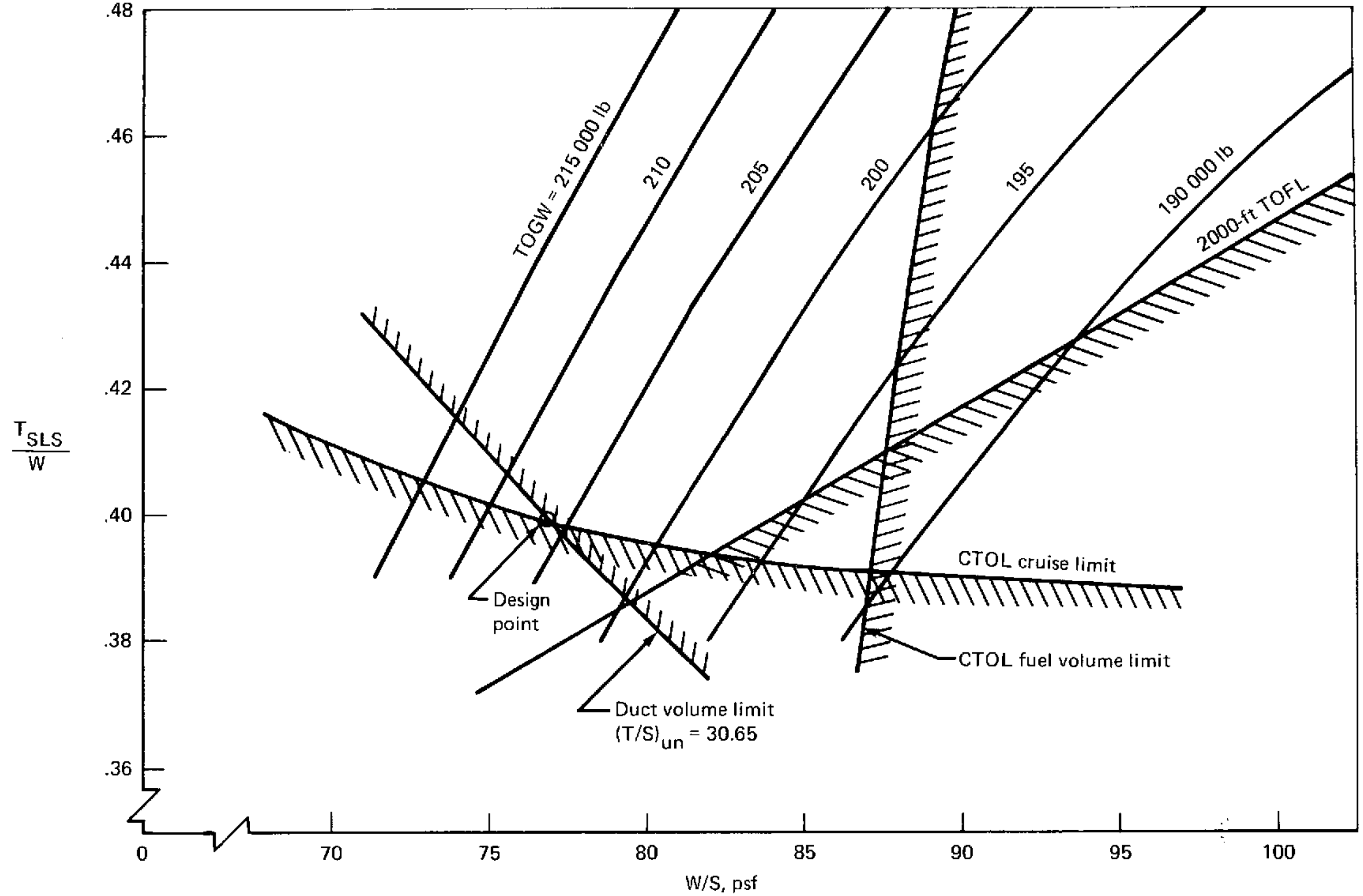


FIGURE 23.—AUGMENTOR WING AIRPLANE SIZING PARAMETERS (AR = 8.0, ΔP/P = 0.12)

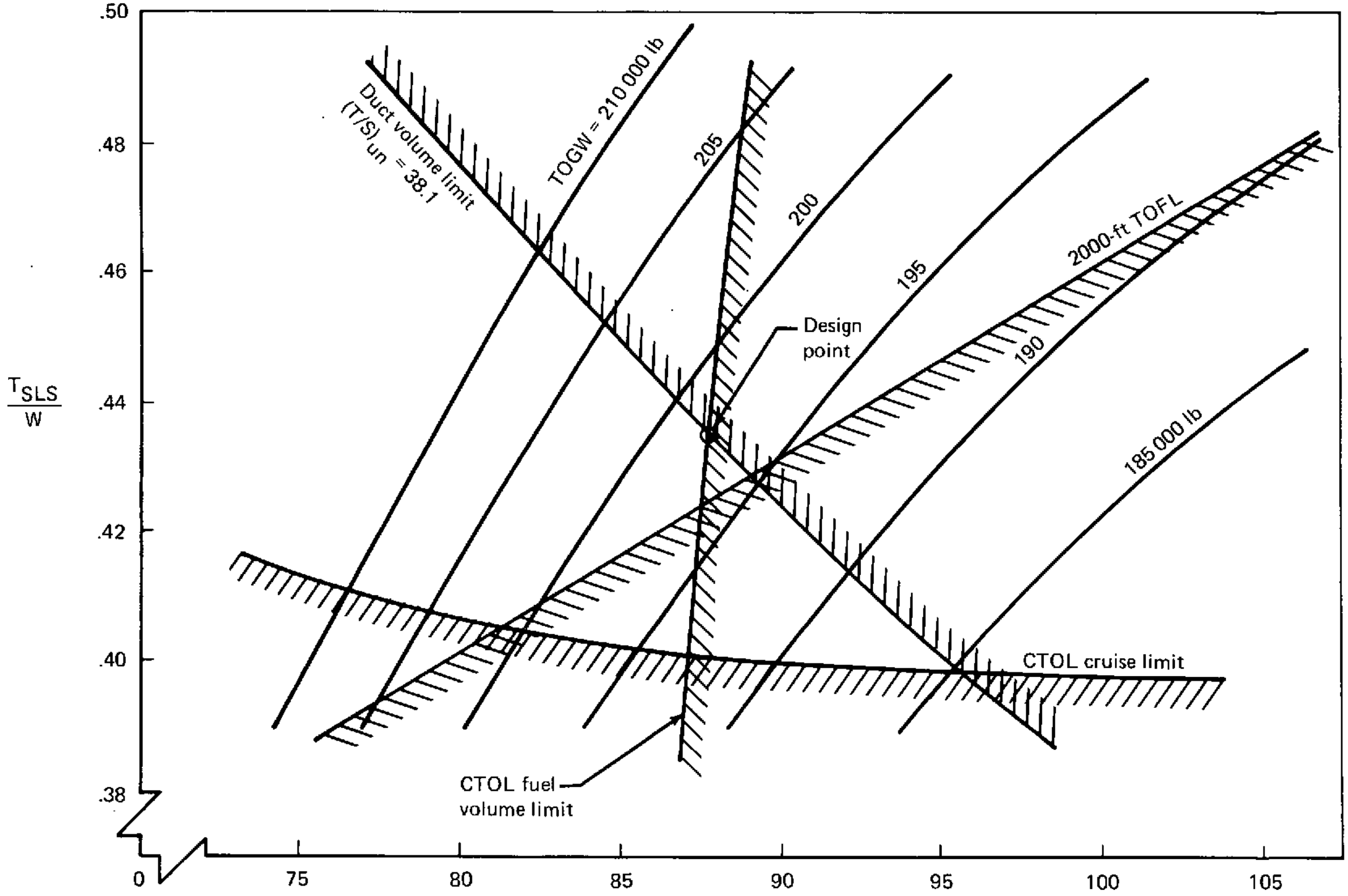


FIGURE 24.—AUGMENTOR WING AIRPLANE SIZING PARAMETERS (AR = 7.5, ΔP/P = 0.12)

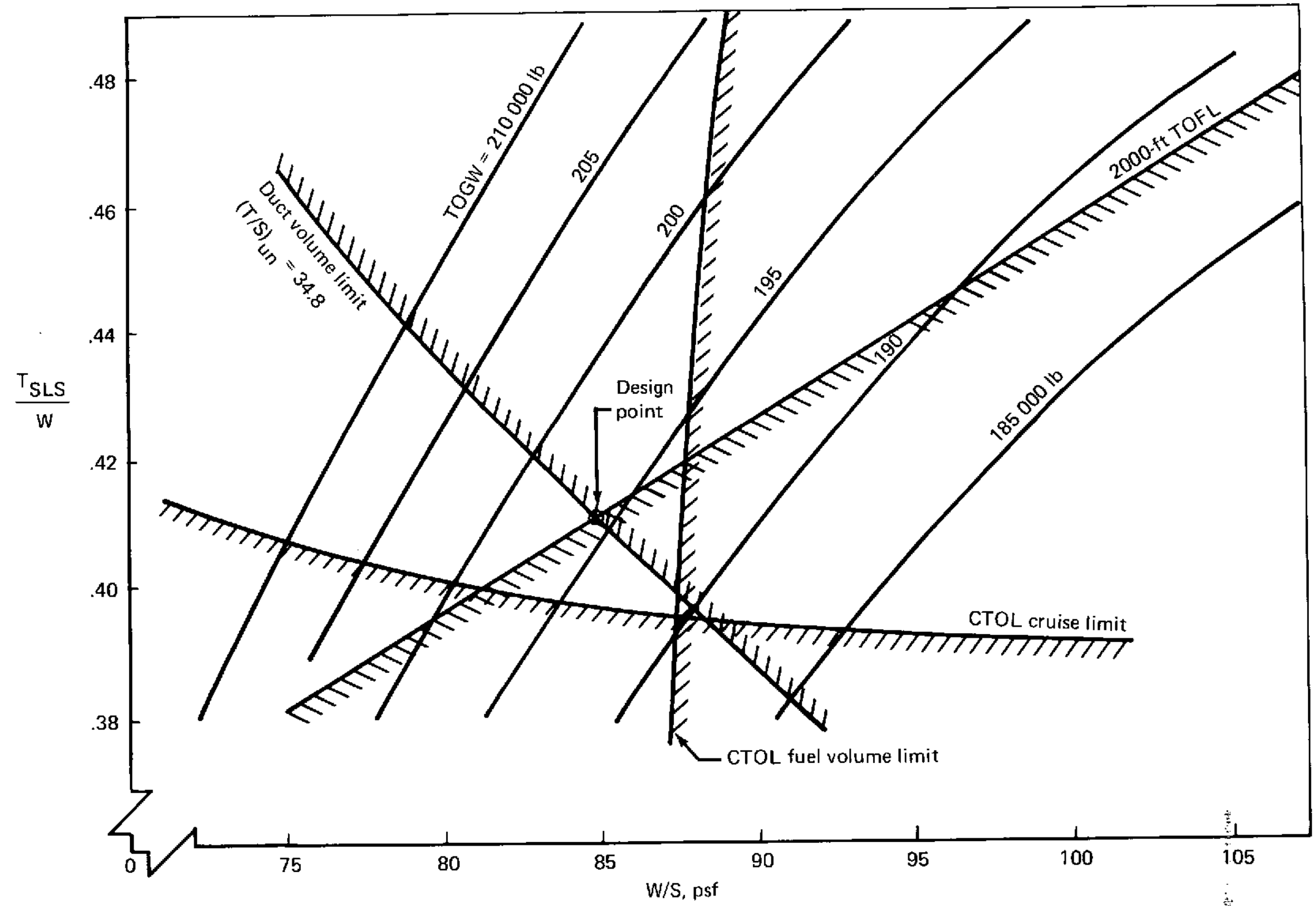


FIGURE 25.—AUGMENTOR WING CRUISE BLOWING SYSTEM AIRPLANE SIZING PARAMETERS (AR = 7.5, $\Delta P/P_F$ = 0.10)

4.4.5 System Integration Summary

Table IV summarizes the effect of wing aspect ratio and duct flow velocity on the updated task VII cruise blowing airplanes. The noise and static augmentation values are for an augmentor system with a flap chord of 0.28c and augmentor nozzle parameters of AAR = 6.0 and H/P = 1.6.

TABLE IV.–TASK VII CONFIGURATION CHOICE (1978 TECHNOLOGY)

Config	AR	$\Delta P/P_F$	TOGW	T/S	T/W	W/S	S_W	A_N/S	$L/h_{\bar{E}}$	ϕ^a	PNdB
1[b]	8.0	0.10	227 700	28.0	0.412	68.1	3343	0.565	56.9	1.24	86.5
2[b]	8.0	0.12	205 300	30.65	0.398	76.8	2674	0.631	50.9	1.22	88.0
3[c]	7.5	0.12	198 000	38.1	0.435	87.6	2259	0.85	41.0	1.19	92.0
4	7.5	0.10	195 800	34.8	0.411	84.8	2309	0.702	45.8	1.20	90.0

[a]ϕ includes 0.05 for future developments.

[b]Thrust determined by CTOL initial cruise requirements.

[c]Wing size determined by CTOL fuel volume requirements.

Comparison of configurations 1 and 2 shows that increasing duct thrust capacity of an AR = 8.0 wing by increasing duct flow velocity allows a much smaller wing and a larger reduction in TOGW. The higher thrust loading causes a 1.5-PNdB noise increase and an augmentation decrease of $\Delta\phi$ = -0.017 because of the lower value of $L/h_{\bar{E}}$. Configurations 2 and 3 show the effect of lowering the wing aspect ratio at constant duct pressure loss. The reduction in wing size allowed by the higher duct thrust capacity of the AR = 7.5 wing is restricted by the CTOL fuel volume requirements, but the resulting wing area of 2259 sq ft and the higher thrust loading causes noise to increase 4 PNdB and augmentation to decrease by $\Delta\phi$ = -0.032. The duct flow velocity of configuration 4 is slowed to that associated with $\Delta P/P$ = 0.10 to establish the effects of lower wing and thrust loadings at AR = 7.5. The smaller A_N/S and larger $L/h_{\bar{E}}$ decrease noise by 2 PNdB to the goal of 90 PNdB. The improved augmentation and reduced duct pressure losses offset the higher wing weight, and the resulting TOGW is slightly less than that of configuration 3. Configuration 4 is the recommended choice because it meets the 90-PNdB noise goal and has the lightest TOGW. Major characteristics and a weight breakdown for configuration 4 are given in table V.

TABLE V.–RECOMMENDED TASK VIIA CONFIGURATION

Major characteristics	
CTOL gross weight, lb	241 900
STOL gross weight, lb	195 800
Thrust/weight	0.411
Wing sweep at c/4, deg	25
Wing taper ratio	0.30
Wing t/c	0.176 to 0.132
Wing loading, W/S, psf	84.8
Aspect ratio	7.5
Wing area, S_W, sq ft	2309
Horizontal tail volume coefficient	1.07
Vertical tail volume coefficient	0.108
CTOL block fuel, lb	57 390
CTOL reserve fuel, lb	19 130
STOL block fuel, lb	19 320
STOL reserve fuel, lb	10 440
Fuel capacity, lb	81 000
Wing thrust loading, T/S, psf	34.8
Augmentor length ratio, L/h_E	45.8
Nozzle area array ratio, AAR	6.0
Nozzle height/pitch ratio, H/P	1.6
Static thrust augmentation	1.20
Breakdown of weights, lb	
Wing	28 570
Remaining airframe	45 320
Community noise attenuation (lining, etc.)	2 000
Augmentor air system	6 940
Total propulsion	20 260
Total fixed equipment	28 540
Manufacturer's empty weight	132 830
Standard operational items	3 650
Operating empty weight	136 480
Zero fuel weight	181 930
Landing weight	176 920

5.0 CONCLUSIONS

Integration of task VII test results, together with adjustments of duct, nozzle, and flap dimensions, have confirmed the preliminary selection of airplane characteristics made in the reference 1 exploratory design studies.

- The valveless-design augmentor wing airplane, compared with the previous design with valves as described in references 2 and 6, exhibits a significant simplification in system design and operation and achieves this with a small reduction in TOGW. The latter effect results from increased available duct volume, which compensates for other system penalties.

- The optimum wing aspect ratio for minimum takeoff gross weight and noise for the augmentor system studied is approximately 7.5. Increasing the aspect ratio to 8.0 reduces noise, but causes substantial weight increase.

- The cruise blowing nozzle array area ratio is reduced from 8.0 to 6.0 and the flap chord is increased from 0.26c to 0.28c to achieve the goal of 90-PNdB peak noise on the 500-ft sideline in the recommended airplane.

- The combined parasitic and jet efflux scrubbing drag (ΔC_D = 0.0025) attributed to the cruise blowing nozzles is approximately double that assumed in reference 1 for the same nozzle configuration. Adjustment of the nozzle array area ratio from 8.0 to 6.0 reduces the drag increment to ΔC_D = 0.0021, with an increased nozzle weight of 270 lb.

- Adjustments in air distribution system flow loss assumptions reflecting flow rig test results reported in reference 5, combined with minor area increases in critical duct sections, result in a net decrease in available wing thrust loading, $(T/S)_{un}$, from 36.0 to 34.8 psf at duct flow velocities corresponding to $\Delta P/P_F$ = 0.10.

- Static thrust augmentation, revised to reflect static test results of references 2 and 4 as well as the decrease in nozzle array ratio to 6.0, is reduced to 1.20 compared with 1.30 used in reference 1. This net change results from the combined effects of:

  - Accounting in the gross static augmentation level for the effect of heated primary air and for the deterioration of augmentation in the corrugated nozzle needed to achieve the 90-PNdB noise goal

- The lower inherent augmentation of the array ratio = 6.0 nozzle (compared with AAR = 8.0) required to meet the noise goal

- A substantial increase in flow turning losses with flap deflection, attributed to the secondary fairing configuration of the cruise blowing nozzle

- The characteristics from the two studies are compared as follows:

	Reference 1	Current
TOGW, lb	191 500	195 800
Wing loading, W/S, psf	84	84.8
Wing aspect ratio, AR	7.5	7.5
Wing sweep angle (0.25c), deg	25	25
Wing thickness, t/c	$0.132_{outboard}$, 0.176_{SOB}	$0.132_{outboard}$, 0.176_{SOB}
$SLST_{(un)}$, each of four engines, lb	18 300	20 120
Peak noise at 500-ft sideline, PNdB	90	90

Boeing Commercial Airplane Company,
P.O. Box 3707,
Seattle, Washington 98124, April 1973.

REFERENCES

1. Roepcke, F. A.; and Nickson, T. B.: *Design Integration and Noise Studies for Jet STOL Aircraft; Task VIIA, Augmentor Wing Cruise Blowing Valveless System. Volume II–Design Exploration.* NASA CR-114570, April 1973.

2. Campbell, J. M.; Harkonen, D. L.; Lawrence, R. L.; and O'Keefe, J. V.: *Design Integration and Noise Studies for Jet STOL Aircraft; Task V, Noise Suppression of Improved Augmentors for Jet STOL Aircraft.* NASA CR-114534, January 1973.

3. Mahal, A. S.; and Gilchrist, I. J.: *Design Integration and Noise Studies for Jet STOL Aircraft; Task VIIB, Augmentor Wing Cruise Blowing Valveless System. Wind Tunnel Investigation of a 14-Percent Thick Airfoil With Upper Surface Blowing at High Subsonic Mach Numbers.* NASA CR-114560, January 1973.

4. Campbell, J. M.; Harkonen, D. L.; and O'Keefe, J. V.: *Design Integration and Noise Studies for Jet STOL Aircraft; Task VIIC, Augmentor Wing Cruise Blowing Valveless System. Volume I–Static Testing of Augmentor Noise and Performance.* NASA CR-114622, March 1973.

5. Runnels, J.; and Gupta, A.: *Design Integration and Noise Studies for Jet STOL Aircraft; Task VIIC, Augmentor Wing Cruise Blowing Valveless System. Volume II–Small Scale Development Testing of Augmentor Wing Critical Ducting Components.* NASA CR-114623, August 1973.

6. Roepcke, F. A.: and Kelley, G. S.: *Design Integration and Noise Studies for Jet STOL Aircraft. Volume II–System Design and Evaluation Studies.* NASA CR-114472 (originally issued as CR-114284), May 1972.